Effects of Manure Application upon Water Quality of Surface Runoff from Rainfall Simulation Tests

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ABSTRACT

Manure contains nutrients for crop growth; however, overapplication, with time, can result in excess nutrients in soil, which can subsequently be lost in surface runoff.

The general purpose of this research is to study the effect of liquid hog manure, applied as an agricultural fertilizer, on water chemistry of surface runoff from rainfall simulation tests. Specifically the research focuses on runoff water chemistry comparisons between lands receiving hog manure at different rates, via different injection methods, and upon different slope positions.

To examine these objectives, soil nutrient supply rates (P, NH_4-N, and NO_3-N) of the 0 – 5 cm depth of soil adjacent to rainfall simulation positions, and runoff water chemistry (TP, OP, NH_4-N, NO_3-N, DOC, Cl^- and coliforms) during rainfall simulation tests were collected before and after manure addition.

Generally, manure application did increase soil NH_4-N and NO_3-N supply rates, and runoff NH_4-N concentration. Soil P supply rate and runoff TP concentration were not affected by the manure addition; however, runoff OP concentration at one site (Perdue) increased significantly due to manure addition. The manure treatments applied in this study did not cause any significant increases in fecal or total coliform in runoff from rainfall simulation tests conducted 7 – 8 months after manure application. None of the water quality parameters exceeded the Guidelines for Canadian Drinking Water Quality.

Manure injection method (regular versus low soil surface disturbance) had consistent effects on runoff chemistry, but application rate did not. The regular disturbance method had significantly higher concentrations of water quality parameters than the low disturbance method.

The position of the test on the slope did not result in any consistent trends in runoff chemistry, whether before or after manure addition. Foot slope positions had higher soil NH_4-N supply rates than upper slope positions, both before and after manure

addition. Soil NH_4-N, NO_3-N, and P supply rates between landscape positions were not likely influenced by manure addition.

Regression tests between soil nutrient supply rates and runoff chemistry indicate that soil NH_4-N supply rates are a good index to predict runoff NH_4-N concentration, but soil P did not predict runoff P.

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DEDICATION

This thesis is dedicated to my mother, Shue-Lian Cheng, my best teacher of life. It is she whom I have always looked up to and grown into.

僅將此論文獻給我的母親，鄭淑蓮 女士，一位兼具堅強與柔韌的生活哲學導師，我人生路上的典範。

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1. INTRODUCTION

Manure contains nutrients and organic matter and as such has long been used as a major soil amendment and fertilizer for agricultural crops. The nutrients of manure fertilizer provide key elements (such as N, P, K) for crop growth, and the organic matter in manure helps to improve soil structure, moisture-holding capacity, and drainage.

In the past half-century, the specialization of agriculture has increased dramatically and resulted in the separation of crop and livestock production such that farms are specialized as to one or the other. The separation of large-scale crop and livestock production results in livestock producers being dependent upon nearby crop producers to accept their manure. This, in combination with high transport costs, can result in overapplication of manure (exceeding crop uptake) to cropland. Overapplication of manure can cause potential nutrient accumulation in soil and increase nutrients in soil solution with time. These nutrients are at high risk to be lost to leaching or surface runoff. This is a concern to agricultural landowners who can lose fertilizer value of their soils and to those that may receive waters polluted from such activities.

In 1996, agriculture was a major N and P contributor to Canadian aquatic systems, inputting 2 784 000 N tonnes year^{-1} and 442 000 P tonnes year^{-1} to cropland across Canada and resulting in a surplus of 293 000 tonnes N year^{-1} and 56 000 P tonnes year^{-1} after removal by crops (Chambers et al., 2001). A portion of the excess nutrients was potentially available for transport to surface water and ground water in Canada. Therefore, agricultural N and P represent major potential threats to water quality and aquatic ecosystems.

Nitrogen in the form of nitrate (NO_3-N) or nitrite (NO_2-N) at high concentrations can threaten infant health by causing methemoglobinemia, commonly addressed as “blue baby syndrome” (Jasa et al., 1998). In surface water systems, relatively high concentrations of NO_3-N have been found to be non-toxic to many aquatic organisms, such as plants, bottom-dwelling invertebrates, and fish (Chambers et al., 2001). In fact, the average Canadian adult intakes 51 mg of nitrate daily (44.3 mg from food and 6.8 mg from drinking water at concentration of 4.5 mg L^{-1}) (Chio, 1985). However, some research indicates that a concentration of NO_3-N as low as 2.5 mg L^{-1} can generate chronic effects on a number of amphibian species, and that acute effects occur when concentrations reach the range of 13-40 mg L^{-1} (Baker and Waights, 1993; 1994; Hecnar, 1995; Watt and Oldham, 1995). Nitrogen in the form of un-ionized ammonia (NH_3) is not often found at a sufficient concentration in the Canadian surface waters to create great toxicity to invertebrates or fish (Chambers et al., 2001). In spite of this, NH_3 is still the major concern of toxic nitrogen pollution in surface water systems. Concentrations of NH_3 higher than 2 mg L^{-1} can cause toxicity to aquatic animals, depending on species and life stages (Mueller and Helsel, 1996).

Nitrogen is the most limiting element for crop growth. Therefore, manure is often applied at the rate to satisfy nitrogen consumption for crop growth (N-based). Since the N:P ratio in liquid hog manure is lower than required by crops, N-based manure application may lead to P surplus in soil after crop uptake. Because of its low water solubility and high adsorption by soil minerals, P often enters surface water bodies in particulate-adsorbed form, associated with soil erosion (Miller and Gardiner, 1998). Even though phosphorus is not considered a direct threat to human or animal health, phosphorus is the main cause of eutrophication in lakes and rivers (Carpenter et al., 1998). Eutrophication is *"an overabundance of nutrients in water, which causes accelerated algae and aquatic plant growth"* (Miller and Gardiner, 1998). Eutrophication causes the degradation of water quality (e.g. dissolved oxygen, turbidity, odour, and colour), which results in the deterioration of aquatic life, increases the cost of drinking water treatment, and upsetting the aquatic ecosystem (Carpenter et al., 1998; Chambers et al., 2001).

With the knowledge of the benefits from manure application for crop growth and the negative impact of excess nutrients on surface water bodies, it is desirable to encourage a balanced practice to gain the benefits while preventing disadvantages of manure application. The general goal of this thesis is to determine the effect of liquid hog manure, when applied as an agricultural fertilizer, upon surface runoff water quality at two sites in Saskatchewan (Elstow and Perdue).

The specific objectives are:

1. To determine the effect of hog manure application rates, relative to a chemical fertilizer control, on runoff water quality;
2. To determine the effect of soil surface disturbance by different hog manure injection methods, relative to a chemical fertilizer control, on runoff water quality; and
3. To determine the effect of landscape position (i.e. shoulder, back, and foot slope positions) upon runoff water quality as affected by manure application.

Due to the difficulty of obtaining data from natural runoff events, a rainfall simulator was used to apply water under controlled conditions and to obtain runoff. The manure treatments were made using commercial equipment at a field scale, as opposed to a research plot scale. Within fields, treatments were selected as based upon 'watersheds' – areas in which all runoff waters drain to a central point, either an outlet or a central depression. Two sites were selected for this study; one near the town of Perdue, Saskatchewan and the other near the town of Elstow, Saskatchewan, both within an hour drive of Saskatoon, Saskatchewan. At each site a control watershed (receiving only chemical fertilizer in spring) and manured watersheds (receiving chemical fertilizer in spring and hog manure in fall) were established. At Perdue, two manured watersheds (each receiving a different application rate via one type of injection method) were established; whereas at Elstow there were four manured watersheds (receiving two different application rates via two different injection methods). Runoff measurements were collected from a rainfall simulator set at different slope positions along a transect within each watershed.

In this thesis, Chapter 2 gives a background review of infiltration and runoff processes, of liquid hog manure characteristics in Saskatchewan, and finally of influence of chemical and manure fertilizer on surface runoff water quality. In Chapter 3, the study site descriptions are given and methodology of the experiments and analyses are addressed. Chapter 4 provides the results of soil and manure characteristics, and detailed chemical and hydrological results of runoff and surface soil nutrient supply rate data collected during rainfall simulation tests. The effects of different aspects (i.e. method, rate, and landscape position) of liquid swine manure application on soil and runoff nutrient change collected from rainfall simulation tests are discussed in Chapter 5. Chapter 6 contains conclusions responding to the objectives, and recommendations for future work.

2. LITERATURE REVIEW

2.1 Infiltration and Surface Runoff Process

2.1.1 Infiltration and Runoff Mechanics

Infiltration is the process of water entry through the soil surface. The infiltration rate is highest at the start of infiltration and gradually declines with time to a constant rate, named “steady-state infiltration rate” or “saturated hydraulic conductivity” (Fig.2.1). When the water application rate exceeds the infiltration capacity of the soil, the excess water starts to runoff or pond on the soil surface. If an intensive rainfall is applied to a small area during a short time, such as an hour, water loss to evaporation or plant uptake is negligible; therefore, water application can be partitioned into infiltration, surface retention, and runoff. As the infiltration rate declines with time, runoff rate increases with time and eventually maintains at a constant value as “steady-state runoff rate” (Hillel, 1998; Miller and Gardiner, 1998).

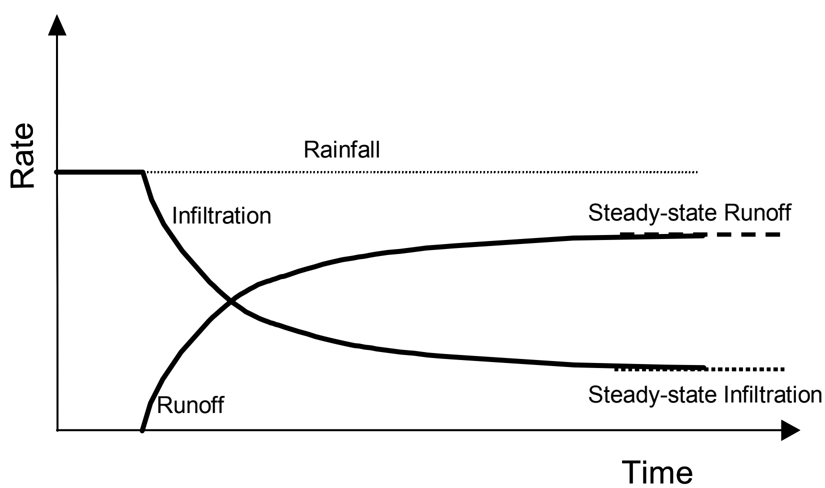


Fig. 2.1: Relationship between rainfall, runoff, and infiltration rate.

If rainfall and infiltration rate are known then runoff is determined by subtracting infiltration from rainfall. Therefore, factors influencing infiltration also affect runoff, including: rainfall intensity and duration, soil hydraulic conductivity and rain impact on the soil surface. Soil hydraulic conductivity is influenced by soil chemical, biological, and physical properties, of which soil moisture content, texture, structure, porosity and surface-open pores may be the most important. In general, runoff tends to be minimized when a low intensity rainfall is applied to a dry sandy soil (i.e. high saturated hydraulic conductivity) with a dense surface residue cover and low slope (Hillel, 1998; Ritter and Berstrom, 2001).

2.1.2 Runoff and Nutrient Redistribution

Surface runoff follows the laws of gravity and flows downhill, and then accumulates in areas where slope changes from steep to level, such as depressions or concave parts of the landscape. While runoff travels across landscapes, it will transport soluble and desorbed chemicals, nutrients, and eroded particulates from surface soil, especially the soil-water interaction zone (1-3 mm depth) (Ahuja et al., 1981; Sharpley, 1985), and later deposit them downstream. Water erosion of surface soil contributes to removal of soil nutrients and organic matter from the upper slope positions to the lower slope positions (Fig. 2.2), or from divergent areas to convergent areas (Bedard-Haughn and Pennock, 2002; Hillel, 1998; Miller and Gardiner, 1998; Pennock et al., 1994).

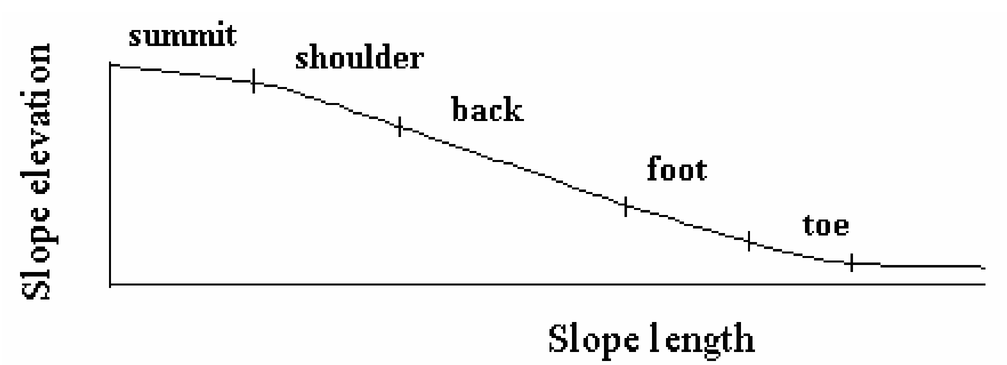


Fig. 2.2: Hillslope elements at different slope positions. Adapted from Pierson and Mulla (1990).

2.2 Liquid Hog Manure Characteristics

Animal manure has long been used as a soil amendment due to its nutrients and organic matter content. Studies have reported that manure N could have N-use efficiency similar to that of chemical fertilizers, and be of more benefit than chemical fertilizers in increasing yield, soil nutrients and improving soil structure. Some studies indicated liquid hog manure to have a fairly high availability coefficient relative to chemical fertilizer, 0.9 (or lower) for N, 0.8 (or lower) for P and K, depending on the application method and incorporation (Barker and Zublena, 1990; Zublena and Barker, 1993). A study in Mississippi by Cushman and Snyder (2002) compared the efficiency of liquid hog manure and soluble chemical fertilizer at an application rate of 134 kg N ha^{-1} yr^{-1}, and concluded that liquid hog manure was an effective source of nutrients compared to soluble chemical fertilizer, and that the different predominant N forms (NO_3-N and NH_4-N in soluble chemical fertilizer; NH_4-N in liquid hog manure) did not affect yield or quality for production of tomatoes. Other research in Quebec by Xie and MacKenzie (1986) compared spring applications of liquid hog manure, fresh and composted cow manure, and urea fertilizer on corn fields at three rates (0, 120, 240 kg N ha^{-1} yr^{-1}), and calculated 1 to 5 kg manure-N (depending on sources) to be equivalent to 1 kg of urea-N in terms of increasing soil NO_3-N levels by the end of growing season. They also found higher total crop N uptake and soil residual NO_3-N with liquid swine manure treatment as compared to cow manure treatments at the same application rate (Xie and MacKenzie, 1986).

In Saskatchewan, liquid hog manure has been commonly utilized as fertilizer, not just because of the increase in swine operations, but because of higher plant-available nutrients relative to solid swine manure, and high moisture content (>90%) for easy handling by pumps (Saskatchewan Agriculture and Food, 1999). However, the low nutrient concentration (content per unit volume) in liquid hog manure limits transport distance due to high transportation costs. Therefore, more than 90% of hog producers in Saskatchewan choose to apply hog manure to croplands in their local region to recycle nutrients back to the crop, as well as to solve manure disposal problems from livestock productions (CETAC-WEST, 2001).

The typical range of nutrient content of swine effluent in Saskatchewan is shown in Table 2.1 (Saskatchewan Agriculture and Food, 2000). Nitrogen is the most abundant nutrient (1,500 – 500 mg L^{-1}) in liquid hot manure, followed by K (800 – 2,000 mg L^{-1}) and P (100 – 2,000 mg L^{-1}). The total nitrogen (TN) of swine effluent is composed of 30% to 90% NH_4-N (readily plant available). Most of the rest of manure N is in the form of organic nitrogen, of which 20% to 30% may become plant available in the year of application through mineralization (Saskatchewan Agriculture and Food, 2000). The study of hog manure nutrient contents in Saskatchewan by Bayne (1997) indicated that manure ammonium (NH_4-N) had a range of 1,400 – 4,000 mg L^{-1} with an average value of 2,400 mg L^{-1} (70 samples collected from 15 lagoons).

Table 2.1: Nutrient contents in liquid swine effluent in Saskatchewan, adapted from Saskatchewan Agriculture and Food (2000).

	Nutrient content (mg L^{-1})	Inorganic Content (% of total nutrient content)
N	1500 – 5000 (TN)	30 – 90% (NH_4-N)
P	100 – 2000 (TP)	10 – 50% (PO_4-P)
K	800 – 2000	N/A
S	10– 300	N/A
Cu	5 – 50	N/A
Mn	5 – 50	N/A
Zn	5 – 100	N/A
B	1	N/A

Note:
- To obtain P_2O_5 value, multiply P by 2.3; to obtain K_2O value, multiply K by 1.2.
- TN: total nitrogen; TP: total phosphorus.

Total phosphorus (TP) content is highly dependant on the solid content of swine effluent, and therefore has a much wider range than the range of N content. Ten to 50% of TP is soluble inorganic PO_4-P, which is immediately plant available. Most of the rest of TP is composed of solid or organic-bonded P, which gradually becomes plant available via decomposition. During the year of application, the availability of manure P is estimated at about half of chemical fertilizer P at the same application rate, and declines when readily soluble manure P content decreases. In conventional N-based manure nutrient management, the great variation of P content in swine effluent has always been a challenge to reach the balance between meeting crop growth need of N and avoiding possible excess P accumulation in soil (Saskatchewan Agriculture and Food, 2000).

In Canada (1996), chemical fertilizer was typically applied to cropland at rates of 60 – 86 kg N ha^{-1} yr^{-1} and 10 –33 kg P ha^{-1} yr^{-1}; whereas manure fertilizer was normally applied at rates of 114 – 301 kg N ha^{-1} yr^{-1} and 38 – 184 kg P ha^{-1} yr^{-1} (Chambers et al., 2001). The report from Saskatchewan Agriculture and Food (Perspectives, 2001) suggested an annual liquid hog manure N loading ranging from 56 to 168 kg N ha^{-1} for several soil climatic zones in Saskatchewan (Table 2.2). For liquid hog manure, an application of 56 kg N ha^{-1} in a single year is insufficient to meet crop needs, but a single application of 112 kg N ha^{-1} one year in two or 168 kg N ha^{-1} one year in three can be acceptable, due to the combination of readily and slowly released plant-accessible nutrients. The report also suggested that manure application should depend on soil test limits, ranging between 84 – 168 kg N ha^{-1} (0-30 cm depth soil sample) for various soils receiving manure in Saskatchewan (Table 2.3). Once soil test N reaches the limit, the manure application rate should be adjusted to avoid nutrient accumulation in soil (Perspectives, 2001).

Table 2.2: Recommended annual liquid hog manure N loading rates for different soil climatic zones in Saskatchewan (Perspectives, 2001).

Soil Climatic Zone	Annual N rate (kg N ha^{-1})
Dry Brown	56
Brown	67
Dark Brown & Moist Dark Brown	78
Black & Moist Black	90
Grey	101
Irrigated	112

Table 2.3: Nitrogen soil test limits (0 – 30 cm) for land receiving manure in Saskatchewan (Perspectives, 2001).

Soil	Soil NO_3-N Limit (kg ha^{-1})
Brown & Dark Brown	84
Black	112
Grey	140
Irrigated	168

2.3 Impacts of Fertilizer Applications on Runoff Water Quality

2.3.1 Nitrogen

Nitrogen Use as Fertilizer

Nitrogen (N) is the major element in the composition of plant proteins, chlorophyll (important in photosynthesis for green plants), nucleic acids (DNA, RNA), and other plant substances; therefore, it is the most limiting nutrient for crop growth (Miller and Gardiner, 1998). Environment Canada (2001a) reported that municipal, industry, agriculture, aquaculture, and atmospheric deposition were the recognized sources of N loading to surface water and groundwater in Canada. In 1996, 2 784 000 tonnes of N, including manure and chemical fertilizer, were added to 35 million hectares of cropland across Canada, resulting in an average N surplus of 8.4 kg ha^{-1} after crop removal. This surplus of N may be lost to the atmosphere, be transported to surface or ground water, or accumulate in soil but the proportions for each cannot yet be estimated (Chambers et al., 2001; Environment Canada, 2001a).

Nitrogen Input and Impact to Surface Runoff Water Quality

Nitrogen can enter aquatic systems from airborne, surface, underground, and *in-situ* sources. Most of the agricultural N entering lakes and rivers is associated with eroded sediments (particle adsorbed NH_4-N) and eroded soil organic matter (organic bonded N and NH_4-N), or in soluble form as NO_3-N in surface runoff (Follett, 2001).

The two major forms of N pollutant, soluble and particulate-associated, determine the mobility and their path to enter surface waters. Due to the negative charge, soluble NO_3-N is highly mobile in soil and can be leached through soil to ground water or drains. Any NO_3-N that does not leach below the soil-runoff interaction zone and is not used by plants is available for transport in surface runoff. In contrast to NO_3-N, NH_4-N is pretty much immobile in soil due to its positive charge associated with high soil adsorption, and therefore is not a concern for groundwater N pollution. However, NH_4-N can be lost to atmosphere through volatilization in the form of $NH_{3(gas)}$

or to surface water bodies in the form of soil-adsorbed NH_4-N on eroded particulates (Follett, 2001).

Nitrate (NO_3-N) concentrations greater than 10 mg NO_3-N L^{-1} are a health concern for human infants (Jasa et al., 1998), while concentrations as low as 2.5 mg NO_3-N L^{-1} can generate chronic effects on a number of amphibian species with acute effects occurring at concentrations between 13 and 40 mg NO_3-N L^{-1} (Baker and Waights, 1993; Baker and Waights., 1994; Hecnar, 1995; Watt and Oldham, 1995). The guideline for Canadian Drinking Water Quality allows the maximum concentrations for nitrite and nitrate together to be 45 mg L^{-1} in drinking water with nitrite lower than 3.2 mg L^{-1} (Environment Canada, 1992a).

Concentrations of un-ionized ammonia (NH_3) higher than 2 mg NH_3 L^{-1} can be toxic to aquatic animals depending on species and life stages (Mueller and Helsel, 1996). However, NH_3 in the Canadian surface waters is not often found at concentrations high enough to create great toxicity to invertebrates or fish (Chambers et al., 2001).

Nitrogen pollution in surface water bodies is one of the major contributors to eutrophication. Eutrophication is *"an overabundance of nutrients in water, which causes accelerated algae and aquatic plant growth"* (Miller and Gardiner, 1998). Eutrophication causes decreased dissolved oxygen, and increased turbidity, odour, and colour), which results in the death of aquatic organisms, upsets the aquatic ecosystem, and increases the cost of drinking water treatment (Carpenter et al., 1998; Chambers et al., 2001). Sawyer (1947) was the first to suggest that inorganic N concentration above 0.3 mg N L^{-1} in surface waters could cause algal blooms.

Effects of Fertilizer on Soil and Runoff N

Different types of soil amendments, even at equivalent rates of N, can result in different levels of N in runoff. A study in Arkansas by Edwards and Daniel (1994) compared surface applied poultry litter, poultry manure, swine manure, and mixed chemical fertilizer to a control (no fertilizer treatment) at the equivalent N application rate. They found that runoff (from rainfall simulation tests conducted 7 days after fertilizer application) of the chemical fertilizer treated plot had the highest concentrations of NH_3-N, followed by liquid swine manure, poultry litter, and poultry manure slurry (Edwards and Daniel, 1994).

High application rates of manure or chemical fertilizer can result in increasing the soil N level, especially for surface soil (Ritter and Berstrom, 2001). A three-year study in Quebec by Warman (1986) examined the effects of applications at different rates from chemical fertilizer (110 and 220 kg N ha^{-1} yr^{-1}), pig manure (198 and 396 kg N ha^{-1} yr^{-1}), and sewage (212 and 424 kg N ha^{-1} yr^{-1}) on NO_3-N in surface soils (sandy loam and clay loam, 0 – 15 cm). In the sandy loam soil, the pig manure and sewage at the high rate resulted in significantly higher (α=0.05) soil NO_3-N (4.1 and 3.6 mg NO_3-N kg^{-1} respectively) than all other treatments (0.3 – 1.6 mg NO_3-N kg^{-1}); in the clay loam soil, pig manure at the high rate resulted in highest soil NO_3-N (2.7 mg NO_3-N kg^{-1}), followed by chemical fertilizer at high rate (1.6 mg NO_3-N kg^{-1}), than all other treatments (0.1 – 1.1 mg NO_3-N kg^{-1}). An 11-yr study in North Carolina by King et al. (1990) examined the effect of land application of swine effluent on soil nutrients at three application rates (335, 670, 1340 kg N ha^{-1} yr^{-1}) and found that the two lower rates resulted in 1 – 5 mg NO_3-N kg^{-1} of water-extractable NO_3-N in soil, which was similar to results where no manure applied, and that the highest rate elevated soil NO_3-N level to 540 kg NO_3-N ha^{-1} in a 2.1 m profile and resulted in N leaching losses.

Plant available N content in manure is often underestimated and therefore is often applied at rates exceeding crop N demand as an insurance (Jackson et al., 2000). Over application of manure can increase N accumulation in soil, which consequently raises the risk of excess soil N loss to surface runoff. Westerman et al. (1987) applied swine lagoon effluent (600 and 1200 kg N ha^{-1} yr^{-1}), swine manure slurry (670 kg N ha^{-1} yr^{-1}), and chemical fertilizer (201-34-65 kg N-P-K ha^{-1} yr^{-1}), and found high N concentrations in natural surface runoff (4 – 13 mg L^{-1}). Other research by Westerman et al. (1985) applied swine lagoon effluent at three different rates (335-90, 670-180, and 1340-360 kg N-P ha^{-1} yr^{-1}) on Coastal Plains soils weekly during the growing season, and examined the effects of application rate on natural runoff water quality. They found that the nutrient concentrations in runoff from all three treatments were as high as 2.8 – 6.4 mg L^{-1}. The hog manure application rates used by King et al. (1990), and Westerman et al. (1987; 1985) were much higher than the recommended rates in the Canada (114 – 301 kg N ha^{-1} yr^{-1}).

Literature has pointed out the effect of incorporation of fertilizer into soil on soil and runoff N. A study in Minnesota by Timmons et al. (1973) applied granular chemical fertilizer with different incorporation methods (Table 2.4), and found that deep-incorporation of chemical fertilizer (plowing down and disking) could effectively minimize N losses in surface runoff to the level of that from the disked unfertilized plots.

The timing of rainfall can also affect runoff N level. A 12-year study in Iowa by Balkcom et al. (2003) monitored soil N and cornstalk N of chemical fertilized, and combined fertilized (chemical and swine or cattle manure fertilizer) fields at rates of 150-164 kg N ha^{-1} yr^{-1}, and then analyzed the natural rainfall (amount and time) effects on soil N and cornstalk N, and NO_3-N concentrations in nearby rivers. They found that N loss caused by early-season (March – May) rainfall was the most important factor influencing the crop growth N sufficiency and NO_3-N concentration in rivers. With these findings, they suggested that fertilizer use efficiency could be increased (consequently reducing the excess N loss to surface water) by delaying fertilizer application till shortly before crop growth, and by decreasing fertilizer application rate to avoid application of N in excess of plant uptake requirement (Balkcom et al., 2003).

2.3.2 Phosphorus

Phosphorus Use as Fertilizer

Phosphorus (P) is one of the essential nutrients for plant growth, and it has long been recommended to be included in soil amendments to achieve profitable crop production (Hedley and Sharpley, 1998). In Canada, the recognized sources of P loading to surface water and groundwater are municipal, industry, agriculture, aquaculture, and atmosphere deposition (Environment Canada, 2001a). In 1996, 442 000 tonnes of P were added to 35 million hectares of cropland across Canada, resulting in an average P surplus of 1.6 kg ha^{-1} after crop removal. This surplus of P may accumulate in soil, or may be transported in soluble or particulate-associated forms to surface waters (Chambers et al., 2001).

Phosphorus in liquid hog manure mostly exists in solid form and, therefore, manure P is not completely available for plant uptake, as compared to chemical fertilizer P, in the season following application (Barnett, 1994; Saskatchewan Agriculture and Food, 2000). However, the 24-yr study by Smith et al. (1998) in the United Kingdom reported that manure P and chemical fertilizer P could be considered as equivalent to each other in the long term.

The N:P ratio for common crop growth is around 1:0.17 (Perspectives, 2001), but the average N:P ratio of liquid hog manure in Saskatchewan ranges from 1:0.07 to 1:0.4, using data from Table 2.1. The manure application rate based on N removal level of crops (N-based) could result in over application of P according to crop demand, even though the applied P might not be rapidly plant-accessible (Perspectives, 2001). Moreover, due to great variance of nutrient content in manure, manure is often applied at a surplus rate as insurance to ensure N and P demands of crop growth are satisfied (Jackson et al., 2000). The application rate of chemical fertilizer can also exceed the suggested rate, as insurance against low plant-availability due to high sorption of P by soil minerals.

Phosphorus Input and Impact to Surface Runoff Water Quality

Phosphorus is less mobile in soil than NO_3-N due to high adsorption by soil minerals. Phosphorus is bound to Al or Fe oxides and hydrous oxides in acid soils and to $CaCO_3$ in alkaline soils (Morgan, 1997; Reddy et al., 1980; Robinson and Sharpley, 1996). As a result of the low solubility, surface applied fertilizer P usually does not move from surface into deep soil, but remains near the soil surface where it can be transported in particulate-associated (sediment-bound) and soluble forms in surface runoff (Sharpley and Menzel, 1987). If P accumulation exceeds the soil retention capacity, P mobility increases, resulting in increasing transport of soluble P in surface runoff (Holford et al., 1997). The review by Sharpley and Menzel (1987) indicated that soil P losses from cultivated land is more particulate P than soluble P, due to higher soil erosion as compared to pasture or forest land.

The pathways of P loss to surface water bodies are mainly soil erosion, surface runoff, subsurface drainage, and stream flow. Phosphorus is not considered a direct threat to human or animal health; therefore, the Canadian Water Quality Guidelines (Environment Canada, 2004) does not include P. However, P is usually the nutrient limiting eutrophication in lakes and rivers (Carpenter et al., 1998). Sawyer (1947) was the first one to suggest that inorganic P concentrations above 0.015 mg P L^{-1} could cause algal blooms. The Surface Water Quality Initiative by the Prairie Farm Rehabilitation Administration of Agriculture and Agri-Food Canada adopted Canadian Drinking Water Quality Guidelines and suggested a drinking water standard for P as 0.010 mg L^{-1} (Corkal, 1997).

Effects of Fertilizer on Soil and Runoff P

A review of literature by Tabbara (2003) indicated that the factors affecting P loss to runoff, as influenced by chemical or manure application, included: P source, P chemical form, tillage and P placement, rate and timing of manure application, intensity and timing of rainfall events, and soil P level.

Manure has been reported to result in lower P losses in runoff than chemical fertilizer. Tabbara (2003) compared two application rates of liquid ammonium polyphosphate fertilizer (94 kg TN ha^{-1} yr^{-1} and 158 kg TP ha^{-1} yr^{-1}; 46 kg TN ha^{-1} yr^{-1} and 74 kg TP ha^{-1} yr^{-1}) to liquid hog manure (305 kg TN ha^{-1} yr^{-1} and 121 kg TP ha^{-1} yr^{-1}; 187 kg TN ha^{-1} yr^{-1} and 62 kg TP ha^{-1} yr^{-1}) using either surface broadcast or incorporated methods of application. He found that 24 hr after the fertilizer treatment, the concentrations of dissolved reactive P, dissolved organic P, and total dissolved P in the runoff from rainfall simulation tests at manure treated sites were significantly lower (α=0.001) than those at chemical fertilizer treated sites, regardless of application method.

Many publications have indicated that over application of manure P is greatly responsible for decreasing soil adsorption capacity, and increasing soil P sorption saturation and accumulation (Nair et al., 1998; Reddy et al., 1980; Sharpley et al., 1984; Siddique and Robinson, 2003; Simard et al., 1995). Over application of P leads to P surplus after crop uptake and results in soil-adsorbed P accumulation. The study in

North Carolina by Reddy et al. (1980) examined the effect of swine lagoon effluent applications on two soils at various rates (650 and 1300 kg N ha^{-1} yr^{-1} on a sandy loam soil for 3 yr; 325, 650 and 1300 kg N ha^{-1} yr^{-1} on a loamy sand soil for 5 yr) and found that as application rate increased, adsorption capacity of soil decreased, and soluble P, acid-extractable P, equilibrium P concentration, and P desorption in soil increased. The long-term effect of P surplus ultimately increases the level of soil P sorption saturation and available P in soil (Tunney et al., 1997).

With the increasing degree of P sorption saturation, more soluble P remains in soil solution (Holford et al., 1997), which is at a high risk of P loss to surface runoff and subsurface flow. An 11-yr study in North Carolina by King et al. (1990) examined the effects of land application of swine effluent on soil nutrients at three application rates (335, 670, 1340 kg N ha^{-1} yr^{-1}, with a P/N ratio = 0.33) and found that the soil P concentrations were directly related to manure application rate in the 0 – 45 cm depth, and soil P concentrations were greater than 45 mg kg^{-1} at all rates of applications.

Various results are reported regarding effects of tillage and incorporation of manure or chemical fertilizer on runoff. The study in Iowa by Tabbara (2003) showed that, as compared to surface broadcast, the incorporation of fertilizer P (either inorganic fertilizer or manure) under conventional tillage (tandem disk) resulted in a 30-60% (depending on the P source as chemical fertilizer or manure) reduction of dissolved reactive P and TP, and an increase of total suspended solids in runoff, which implied higher soil erosion.

Numerous studies have discussed the effects of type and rate of fertilizer application on runoff P. A model was developed by Grant et al. (2004) and tested against P loss in runoff, erosion and leachate with cattle manure applications at different rates for three to six years, using transport and transformation kinetics with different manure application rates. The computer model simulated 60 yrs of P application and showed that cattle manure application rates greater than 30 Mg ha^{-1} yr^{-1} would cause TP concentrations in runoff to exceed acceptable limits. Kleinman and Sharpley (2003) broadcast three types of manure (dairy, layer poultry, and swine) and found that manure application rate (0 – 150 kg TP ha^{-1}), regardless of manure type, was significantly correlated to runoff dissolved reactive P (r^2=0.66 to 0.98 at α=0.001) and TP (r^2=0.50 to 0.96 at α=0.01).

Westerman et al. (1987) applied swine lagoon effluent at rates of 120 and 240 kg P ha^{-1} yr^{-1} and swine manure slurry at a rate of 200 kg P ha^{-1} yr^{-1} and compared this with chemical fertilizer application (34 kg P ha^{-1} yr^{-1}). They found that P concentration in runoff from the chemical fertilizer treatment and the swine effluent treatment at the low rate was not significantly different (α=0.05), and that manure slurry and effluent at high rates resulted in significantly higher (α=0.05) runoff P concentrations than all other treatments (annual mean P concentration in runoff = 5.6 and 7.7 mg L^{-1}, respectively). They also concluded that both surface and groundwater could be polluted by applying manure slurry and effluent at the higher rates used in their study.

A three-year study in Quebec by Warman (1986) compared the effects of chemical fertilizer (22 kg P ha^{-1} yr^{-1}), pig manure (52 and 104 kg P ha^{-1} yr^{-1}), and sewage (95 and 190 kg P ha^{-1} yr^{-1}) applications to a control (no fertilizer treatment) on Bray P_2-extractable P of surface soils (sandy loam and clay loam, 0 – 15 cm). In sandy loam soil, pig manure and sewage at the high rates resulted in significantly (α=0.05) higher soil P (127 and 134 mg kg^{-1} respectively), followed by pig manure at the low rate (soil P of 96 mg kg^{-1}) and then all other treatments (soil P of 54 – 73 mg kg^{-1}); in a clay loam soil, sewage at high rate resulted in significantly higher soil P (144 mg kg^{-1}) than all other treatments (soil P of 81 – 101 mg kg^{-1}).

Phosphorus Limit for Hog Manure Application and Management in Saskatchewan

In arid to semi-arid climate regions of Saskatchewan, where P loss to water bodies via infiltration is unlikely, the major P loss is through soil erosion and runoff to surface water bodies. A review of literature on manure management and application to Saskatchewan conditions by Perspectives (2001) suggested that medium to fine soils in Saskatchewan unlikely have a P leaching problem. Additionally, even if P leaches and moves along with drainage, much of Saskatchewan baseflow enters the nearest slough without direct contact to sensitive water bodies where eutrophication might occur. Therefore, Perspectives (2001) considered N-based manure application suitable for Saskatchewan. Furthermore, Perspectives (2001) anticipated that P limits will unlikely be needed in the near future, and recommended that, even if it will be needed in the future, areas draining directly to sensitive water bodies should be first considered.

The report by Perspectives (2001) also suggested that soil test P in the 0 – 15 cm depth could be an index for manure application limits. When soil P (0 – 15 cm depth) exceeds 60 mg kg^{-1}, limits should be adapted for further P addition according to crop removal of P, and no manure should be applied when soil test P exceeds 100 mg kg^{-1}.

2.3.3 Coliform, Dissolved Organic Carbon, and Chloride

Coliform bacteria have always been a concern for groundwater and surface water quality (Mallin et al., 1997; Mawdsley et al., 1995). Total coliform bacteria are an assortment of generally harmless microorganisms that live in the digestive system of humans and animals to help the digestion of food. Fecal coliform bacterium, one of the subgroups of total coliform bacteria, is present in large numbers in the feces and intestine of humans and other warm-blooded animals, and can transport with excrement into water bodies. Fecal coliform bacteria, with the exception of Escherichia coli (E. coli), are not harmful themselves. However, the presence of a large number of fecal coliform bacteria in water indicates the contamination of water by fecal materials, which means that some pathogens (i.e. disease or illness causing organisms) possibly are also present in the water (Murphy, 2004). Therefore, fecal coliform bacteria are an important indicator of water safety for human and animal consumption. The Canadian guidelines for drinking water quality (Environment Canada, 2001b) permit no coliforms (per 100 mL) to be detected in public, semi-public and private drinking water, while the Canadian guidelines for recreational water quality (Environment Canada, 1992b) allow the maximum limit of 2000 E. coli per liter for E. coli bacteria and fecal coliforms. The study by Wang et al. (2000) compared the effects of type (liquid swine manure and chemical N fertilizer), application rate (336 and 168 kg N ha^{-1}), and application method (surface broadcast and incorporation) of fertilizer on bacteria transport in surface runoff from rainfall simulation tests conducted one to three days after fertilizer application. They found: (a) swine manure resulted in significantly higher concentrations of E-coli than chemical fertilizer; (b) the high rate of manure application had higher E-coli concentrations than the low rate, but the difference was not statistically significant; and (c) surface broadcast liquid swine manure caused significantly higher E-coli concentrations than incorporated manure (Wang et al., 2000).

Dissolved organic carbon (DOC) is an indicator of total organic matter concentration in water. In surface water, organic matter is responsible for water taste, odor, and color. During the process of water treatment, organic material also causes the formation of disinfection by-products such as trihalomethanes (THMs), which are carcinogenic. Organic matter in surface waters, from both internal (excretion and decomposition of organisms) and external (soil runoff and decay of terrestrial vegetation) sources, can be related to bacterial proliferation, which can cause diarrhea, gastro-intestinal problems and other illnesses (Corkal, 1997; Volk et al., 2002). Dissolved organic matter also acts as a strong opponent for soluble pollutants (e.g. pesticides and insecticides) in sorption site competition on soil particle surfaces. Reduced sorption of the pollutants leads to increasing mobility of pollutants in soil (Chiou et al., 1986; Flores-Cespedes et al., 2002; Graber et al., 1995; Nelson et al., 1998). However, in contrast of decreasing sorption of pollutants, literature also has reported increasing sorption and decreased leaching of pesticide due to the application of organic matter as a soil amendment, such as buried straw, digested municipal sewage sludge, and animal manure (Guo et al., 1993; Johnson et al., 1997). Canadian guidelines for drinking water quality did not include DOC, but the Surface Water Quality Initiative suggested that DOC level should not exceed 5 mg L^{-1} in water prior to the chlorination to avoid causing THMs to exceed 100 μg L^{-1} (Corkal, 1997). The report of the Surface Water Quality Initiative (Corkal, 1997) also reported that the DOC concentrations in rural Saskatchewan dugouts (12.8 mg L^{-1}) was significant higher than DOC in Buffalo Pound Lake in Regina (6 – 8 mg L^{-1}), and in South Saskatchewan River in Saskatoon (2 – 4 mg L^{-1}).

Chloride (Cl^-) is highly soluble; however, it does not pose a toxic threat to human or animal health. Chloride in the soil profile comes from various sources, including rainfall, dry fallout, and mineral breakdown (Ward, 2003). Chloride concentrations in natural surface waters in Canada normally are lower than 10 mg L^{-1}, and often lower than 1 mg L^{-1}. In 1975, only one out of 127 stations analyzed for Cl^- in

Saskatchewan reported Cl^- concentrations higher than 50 mg L^{-1}, and no station reported a concentration > 250 mg L^{-1}. The guidelines for Canadian drinking water quality (Environment Canada, 1987) suggest Cl^- to be lower than 250 mg L^{-1} in drinking water to meet the aesthetic objective.

3. SITE DESCRIPTION AND METHODOLOGY

3.1 Study Sites

Two study sites, Perdue and Elstow, were established in 1998 and 1999, respectively. Close to each site there is a hog barn that was established around the same time that the studies began. Both sites are less than one-hour driving distance from Saskatoon, Saskatchewan. The Perdue site is about 70 km west of Saskatoon and the Elstow site is about 50 km south-east of Saskatoon (line distance, Fig. 3.1).

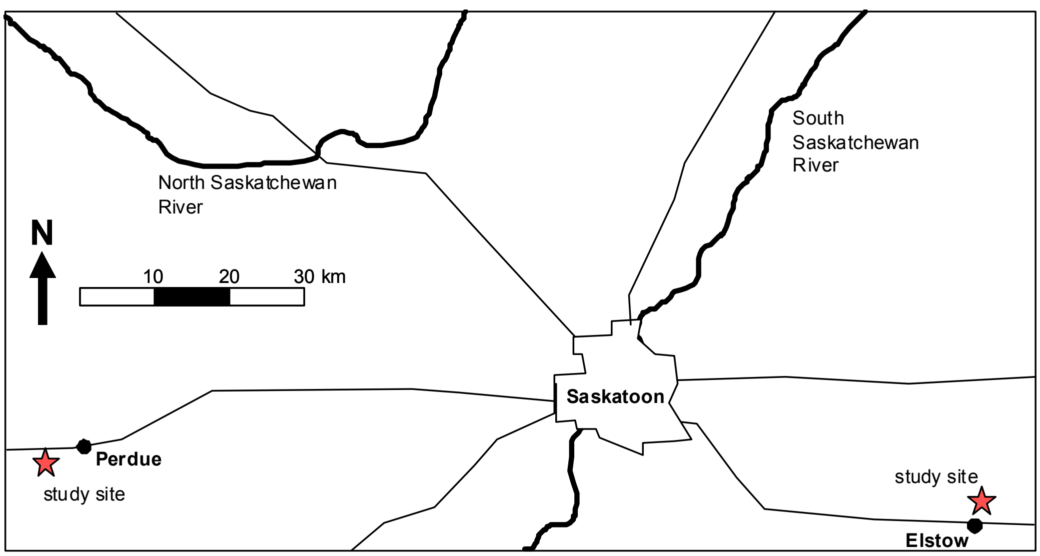


Fig. 3.1: Study site locations near Perdue and Elstow, SK (marked by stars).

3.1.1 Climate

Since both sites are close to Saskatoon, the general climate of both sites can be represented by the climate data taken at the Saskatoon Airport. The long-term climate is described as continental sub-humid to semi-arid, with a mean annual precipitation of 343 mm and a mean annual temperature of 2.3°C (Saskatoon Airport, 1970-2002). The weather during the study period, 1998-2002, was drier and slightly warmer (total annual precipitation = 272 mm; mean annual temperature = 3.0°C) than normal.

The long-term average monthly precipitation and temperature for the periods of 1970-2002 and 1998-2002 are as shown in Fig. 3.2 (Appendix A1 and A2). The monthly mean temperature of 1998-2002 was generally higher than that of 1970-2002, with exception of May, June, and October, when the temperature was 0.3 to 1.3 ^{o}C lower. For both periods, the warmest month was July, and the coldest was January. The greatest difference in monthly mean temperature occurred in November of 1998-2002, when temperature was 2.4^{o}C higher than that of 1970-2002.

The monthly precipitation of 1998-2002 was generally lower than 1970-2002, with the exception of July and August, when precipitation was 6 and 4 mm more, respectively. For both periods, the highest monthly precipitation occurred in June and July, and the lowest monthly precipitation was in February and November. The greatest difference of precipitation between the two periods occurred in May when the precipitation of 1998-2002 was 22.7 mm less than 1970-2002 (Fig. 3.2).

During the study period (1998 – 2002), no major rainfall events were recorded. Therefore, the natural precipitation is not expected to alter the results of rainfall simulation tests being performed during the study period.

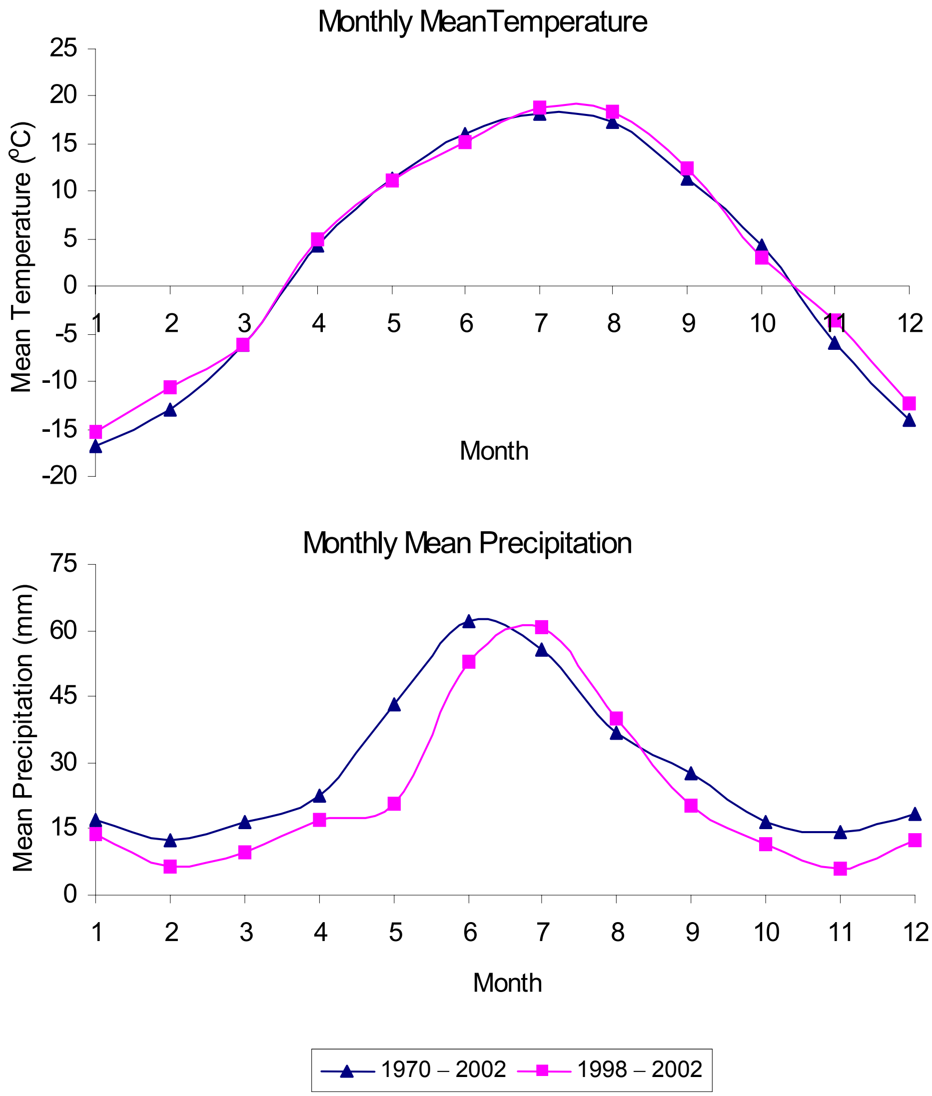


Fig. 3.2: Long term weather data – Saskatoon Airport, SK.

3.1.2 Perdue Site

Three watersheds, named A, B, and C, were chosen and surveyed during the late summer and early fall of 1998. Each watershed was treated with different fertilizer types and/or application rates. Watershed A was the control, treated with conventional chemical fertilizer; watersheds B and C received manure fertilizer for the first time in the fall of 1999 from the Bear Hills hog barn at two different application rates by a low disturbance method, along with spring chemical fertilizer application at a reduced rate. Baseline conditions for soil and surface runoff (from rainfall simulation tests) quality were collected along one transect within each watershed at three slope positions (shoulder, back, and foot) during the fall of 1998 before any manure addition. After the manure addition, the same slope positions were sampled again during the spring of 2000 for soil and runoff quality comparisons.

Site Location and Characteristics

The Perdue site is located about 70 km west of Saskatoon Airport (line distance, Fig. 3.1) near the Bear Hills Pork Producer's barn. The legal locations of each watershed are given in Table 3.1.

Table 3.1: Watershed characteristics – Perdue.

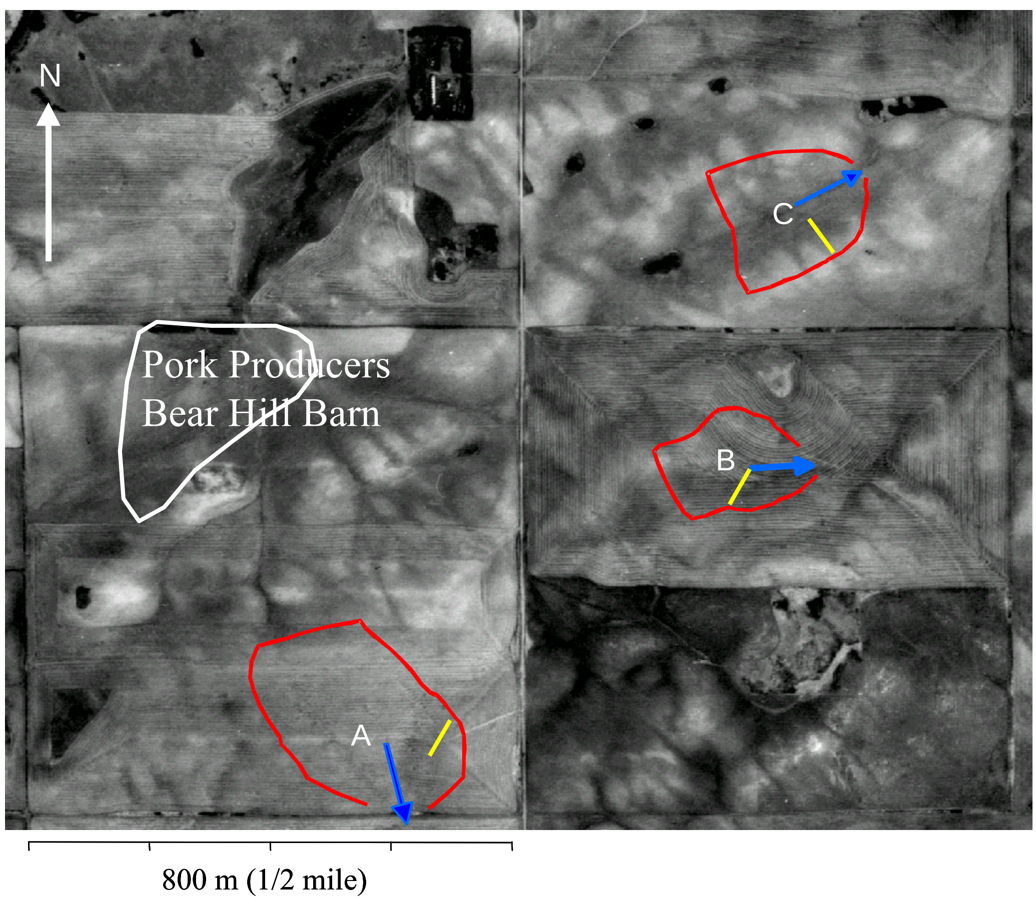
Watershed	Fertilizer treatment	Area (ha)	Elevation change (m)	Slope (%)	General aspect*	Location
A	Chemical fertilizer	6.9	9.8	2.7	SW	NE-28-12-35-W3
B	Manure	4.4	13.0	3.3	SW	NW-27-12-35-W3
C	Manure	6.3	11.9	3.8	E	SW-34-12-35-W3

Note:

- 'Elevation change' refers to the vertical distance between the highest and lowest parts of the landscape within the watershed.
- Slope is calculated as the change in elevation over the length of the transect.
- 'General aspect' is aspect of the sample transect.
- location: quarter-section - township-range-W3 (west of third meridian).
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.

The topography at the Perdue site is generally classified as a dissected landscape with steep slopes, occasionally as steep as 20%, which is close to the upper limit for arable agricultural land in the prairie region. The areas of the three watersheds range from 4.4 to 6.9 hectares, and slopes range from 2.7 to 3.8 % (Fig. 3.3, Table 3.1). All the watersheds at Perdue are externally draining.

The dominant soils at the Perdue site are Dark Brown Chernozemic soils of the Keppel soil association with a mix of highly modified glacial and stratified lacustrine sediments. The steeply sloping landscape suggests that these stratified sediments were deposited in a supra glacial environment. Soil texture of the Perdue site is generally a silt loam to silty clay loam (Ward, 2003).



▪ Blue arrows are the direction of runoff leaving the watershed; yellow lines are transects for soil sampling and the rainfall simulation test locations; white outlined area indicated the location of hog barn.

Fig. 3.3: Location of study watersheds at Perdue (red outline).

Agronomic Practices

Fertilizer treatments were different for each watershed. The fertilizer application history of each watershed at Perdue between 1998 and 2002 is summarized in Table 3.2. Watershed A is the control, where conventional chemical fertilizer was applied during the seeding operation using an air drill along in the spring. In watersheds B and C, liquid swine manure was applied at a rate of 79 m^3 ha^{-1} and 112 m^3 ha^{-1} (converted from 7,000 and 10,000 imperial gal ac^{-1}, Appendix B1), respectively, by a low disturbance injection method on Oct 12, 1999. The low disturbance injection method for watersheds B and C used disk openers followed by knife injectors on the back of a truck, operated by SANDS LTD (Appendix C1). Manure was applied to areas larger than watersheds.

Table 3.2: Chemical and manure fertilizer application – Perdue (1998 – 2000).

Watershed		Spring 1998	Spring 1999	Fall 1999	Spring 2000
A	Fertilizer type	Chemical	Chemical	N/A	Chemical
	[N- P-K]	[50-10-0]	[50-10-0]		[56-10-11]
B	Fertilizer type	Chemical	Chemical	Manure	Chemical
	[N- P-K]	[50-10-0]	[50-10-0]	[220-62-114] (79 m^3 ha^{-1})	[12-5-9]
C	Fertilizer type	Chemical	Chemical	Manure	Chemical
	[N- P-K]	[50-10-0]	[50-10-0]	[308-67-165] (112 m^3 ha^{-1})	[12-5-9]

Note:
- [N- P-K] in unit of kg ha^{-1}
- N/A: no application
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.
- See Appendix B1 for manure nutrient rate conversion.

The crop rotation history at the Perdue site between 1998 and 2000 is summarized in Table 3.3. The fields were direct seeded by an air drill in the spring with no other soil disturbance. Chemical fertilizer was placed with the seed. At harvest, the crop was combined using a straight cut header. In 1999 and 2000 all watersheds were seeded to the same crop, but in 1998 barley was grown in watershed A while CPS wheat was grown in watersheds B and C.

Table 3.3: Crop rotation history – Perdue (1998 – 2000).

Watershed	1998	1999	2000
A	Barley	CPS Wheat	Canola
B	CPS Wheat	CPS Wheat	Canola
C	CPS Wheat	CPS Wheat	Canola

Note:

- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.

3.1.3 Elstow site

Five watersheds, named A, B, C, D, and E, were selected in October 1999 for monitoring at the Elstow site (Fig. 3.4). Each watershed was treated with either a different fertilizer type, rate, or injection method. Watershed A was the control, treated with conventional chemical fertilizer; the other watersheds received chemical and manure fertilizer from the Prairie Swine Center Inc. hog barn at two different application rates by two different injection methods in the fall of 2001. Baseline conditions for soil and surface runoff (from simulated rain) quality were collected at three slope positions (shoulder, back, and foot) along a transect in all five watersheds during fall of 2000 (ACDE) and 2001 (B) before any manure addition. After the first manure addition, the same slope positions were sampled again for soil and runoff quality comparisons during the spring of 2002.

Site Location and Characteristics

The Elstow site is located approximately 45 km southeast of Saskatoon Airport (line distance, Fig. 3.1) near the Prairie Swine Centre (PSC) Elstow Research Farm Inc. Legal locations of the five watersheds are given in Table 3.4.

Table 3.4: Watershed characteristics – Elstow.

Watershed	Fertilizer treatment	Area (ha)	Elevation change (m)	Slope (%)	General aspect	Location
A	Chemical fertilizer	5.6	3.5	2.3	S	SE-27-35-1-W3
B	Manure (Low dis) 56 m^3 ha^{-1}	2.1	2.0	2.0	S	SW-26-35-1-W3
C	Manure (Reg dis) 90 m^3 ha^{-1}	1.9	2.2	2.0	S	SW-26-35-1-W3
D	Manure (Reg dis) 56 m^3 ha^{-1}	1.6	3.0	2.7	N	NE-23-35-1-W3
E	Manure (Low dis) 90 m^3 ha^{-1}	1.6	1.5	2.4	N	NE-23-35-1-W3

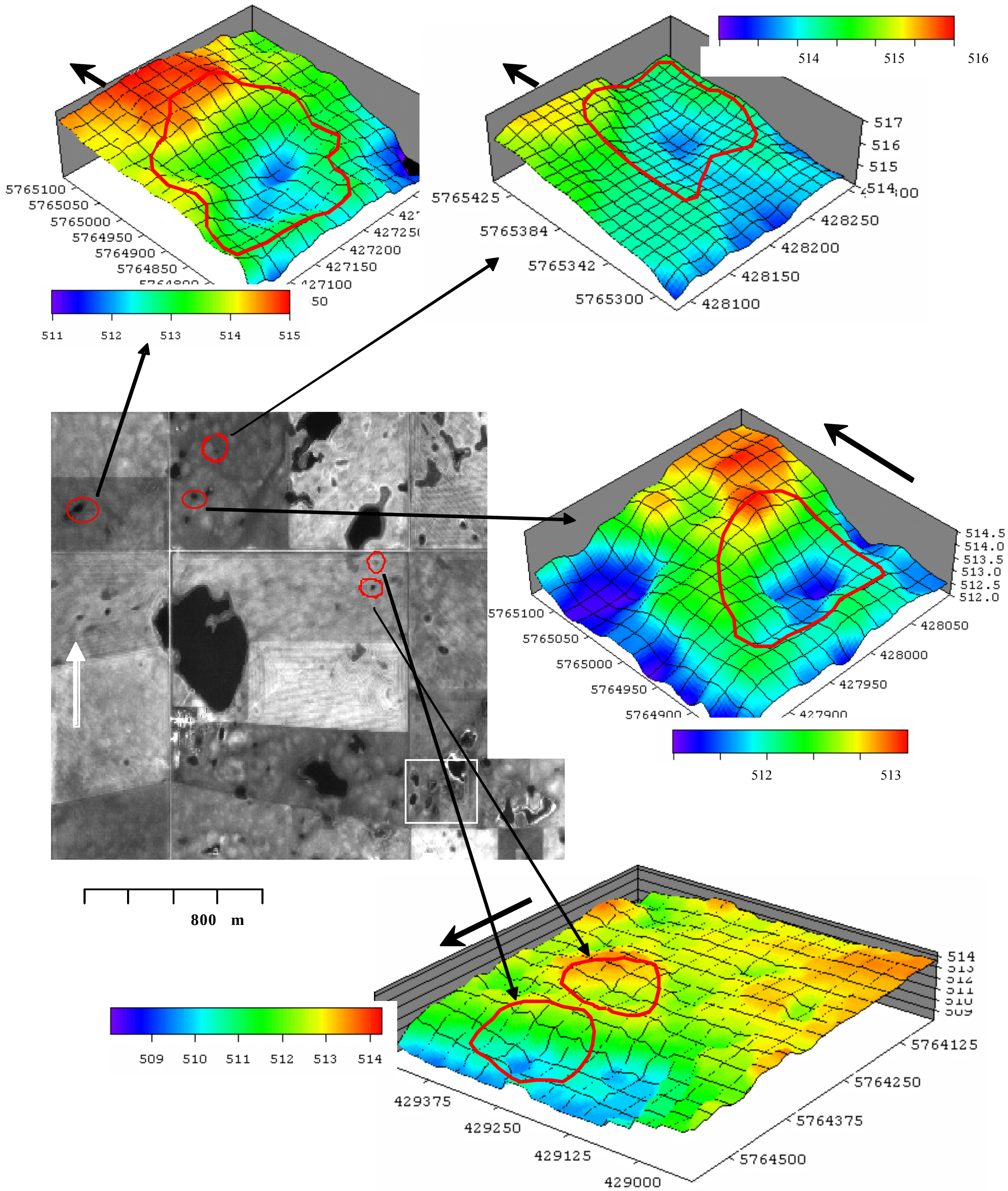
Note:

- ‘Reg’ refers to regular; ‘dis’ refers to the relative amount of disturbance of the injection.
- Watersheds C and D received liquid hog manure by regular disturbance injection method, using shovel openers; watersheds B and E received liquid hog manure by low disturbance injection method, using disc opener in fall 2001.
- ‘Elevation change’ refers to the vertical distance between the highest and lowest parts of the landscape within the watershed.
- Slope is calculated as the change in elevation over the length of the transect.
- General aspect is aspect of sample transect.
- Location: quarter-section-township-range-W3 (west of third meridian).

Landforms in this region are composed of aeolian and till plains, and shallow glacial lacustrine plains with a weak knoll and depression pattern on very gently sloping to gently sloping land. The lacustrine deposits are often less than 1 to 2 m with glacial till or glacial-lacustrine clays lying on top (Saskatoon Soils Map Sheet 73B).

All the watersheds lie within three one-quarter sections that received manure from PSC Elstow Research Farm Inc (Fig. 3.4).

The five watersheds are classified as gently sloping, with slopes ranging from 1.5 to 3.5 %, which is considerably gentler than Perdue (Table 3.1 and 3.4). All the watersheds are internally draining. The soils of the Elstow site are Dark Brown Chernozems of the Keppel soil association with moderate to fine texture. The topsoil (Ah) is 15 to 25 cm thick and is underlain by a medium to highly plastic clay extending 4 to 8 m in depth. Below the clay zone and to the depth of investigation of 15 m is a glacial till, consisting of a variant mixture of gravel, sand, silt and gravel sized particles (UMA Engineering LTD, 1999).



Note:
- All distance units are meters.

Fig. 3.4: Location of Elstow watersheds (red line) and topography.

Agronomic Practices

Fertilizer treatments were different for each watershed. The fertilizer application history of each watershed at Elstow between 1998 and 2002 is summarized in Table 3.5.

Table 3.5: Chemical and manure fertilizer application – Elstow (1998 – 2001).

Watershed		Spring 1998	Spring 1999	Spring 2000	Spring 2001	Fall 2001
A	Fertilizer type	Chemical	Chemical	Chemical	N/A	N/A
	[N- P-K]	[18-36-0]	[18-36-0]	[18-36-0]		
B	Fertilizer type	Chemical	Chemical	Chemical	Chemical	Manure
	[N- P-K]	[18-36-0]	[18-36-0]	[18-36-0]	[18-36-0]	[306-24-132]
C	Fertilizer type	Chemical	Chemical	Chemical	Chemical	Manure
	[N- P-K]	[18-36-0]	[18-36-0]	[18-36-0]	[18-36-0]	[362-51-131]
D	Fertilizer type	Chemical	Chemical	Chemical	Chemical	Manure
	[N- P-K]	[18-36-0]	[18-36-0]	[18-36-0]	[18-36-0]	[270-39-102]
E	Fertilizer type	Chemical	Chemical	Chemical	Chemical	Manure
	[N- P-K]	[18-36-0]	[18-36-0]	[18-36-0]	[18-36-0]	[439-36-172]

Note:
- [N- P-K] in unit of kg ha^{-1}
- N/A: no application
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.
- See Appendix B2 for manure nutrient rate conversion.

Watershed A was the control, which only received conventional chemical fertilizer by an air drill along with seed in the spring. Liquid swine manure was applied, for the first time, to watersheds B, C, D, and E during Oct 29 – 31, 2001. Manure was applied to an area larger than the watersheds. Watersheds B and E were treated with manure at an application rate of 56 and 90 m^3 ha^{-1} (converted from 5,000 and 8,000 imperial gal ac^{-1}, Appendix B2), respectively, using a low disturbance injection method with disc openers operated by PAMI (Appendix C2) to apply the manure 10 to 13 cm below soil surface. Watersheds C and D received manure at an application rate of 90 and 56 m^3 ha^{-1} (converted from 8,000 and 5,000 imperial gal ac^{-1}, Appendix B2), respectively, by a regular disturbance injection method using shovel openers to apply the manure 10 to 13 cm below the soil surface. The regular disturbance injection method with shovel openers (used in watersheds C and D of Elstow) caused more disturbance at the soil surface than the knife injectors (used at Perdue) or disc openers (used in watersheds B and E of Elstow).

There was a visible difference of the soil surface between the low and regular disturbance applications. With the low disturbance application, no manure was observed on the soil surface and odour from the treatments was minimal immediately after application. Some manure was seen on the soil surface with the regular disturbance injection and odour was strong immediately afterwards and still discernible one week later.

The low disturbance manure applications (B and E) were pumped from an un-agitated storage except on October 30 2001 when the storage was agitated and manure was applied on watershed E. Application of manure to watershed E took place during a four-day period. A commercial operator using shovel openers within a one-day period applied agitated manure to watersheds C and D. Agitated manure could contain more phosphorus, associated with more solid manure, than un-agitated manure.

The crop rotation history at the Elstow site between 1998 and 2001 is summarized in Table 3.6. The farming practice at Elstow was reduced tillage, with seeding and chemical fertilizer application done simultaneously by an air drill in the spring with no other soil disturbance. At harvest, the crop was combined using a straight cut header. Watersheds B, C, D, and E had the same crop rotation, but on watershed A canola was grown instead of peas in 1999 and peas were grown instead of canola in other watersheds in 2001.

Table 3.6: Crop rotation history – Elstow (1998 – 2001).

Watershed	1998	1999	2000	2001
A	Wheat	Canola	Barley	Peas
B	Wheat	Peas	Barley	Canola
C	Wheat	Peas	Barley	Canola
D	Wheat	Peas	Barley	Canola
E	Wheat	Peas	Barley	Canola

3.2 Rainfall Simulation Tests and Sampling

The timelines of rainfall simulation tests and manure application at both sites are summarized in Table 3.7. Climate data is common to both sites but all other information (such as location, topography, soil type and texture, fertilizing and cropping history) is site specific.

Table 3.7: Rainfall simulation tests and manure application timelines.

Date	Site/Watersheds	Comments
Sep. 17 - Oct 8 1998	Perdue/ABC	Rainfall simulation tests conducted at three slope positions in each watershed after harvesting.
Oct 12, 1999	Perdue/BC	Manure application at Perdue
May 16 - May 19 2000	Perdue/ABC	Rainfall simulation tests conducted at three slope positions in each watershed after seeding.
Sep. 27 - Oct. 16 2000	Elstow/ACDE	Rainfall simulation tests conducted at three slope positions after harvesting.
Oct. 18 ~ 19 2001	Elstow/B	Rainfall simulation tests conducted at three slope positions after harvesting.
Oct 29 - 31 2001	Elstow/BCDE	Manure application at Elstow
May 8 - May 23 2002	Elstow/ABCDE	Rainfall simulation tests were conducted at three slope positions before seeding, including duplicates (back-2) at back slope positions. Back-2 in watershed D was conducted after seeding.

Note:
- ‘Three slope positions’ refers to shoulder, back, and foot slope positions along a slope transect.

Rainfall simulation tests were conducted at three slope positions (shoulder, back, and foot) on all watersheds at both the Perdue and Elstow sites. In the following sections, ‘BEFORE’ refers to rainfall simulation tests conducted before manure addition, and ‘AFTER’ refers to those conducted after manure addition.

All rainfall simulation tests in BEFORE or AFTER were completed in the same season with the exception of Elstow Watershed B for BEFORE. Due to an on-site fire in 2000, rainfall simulation tests on the watershed B of the Elstow site were postponed to fall 2001. One rainfall simulation test was conducted at each slope position in each watershed of each site. However, one additional rainfall simulation test (back-2) was made at the back slope positions in AFTER at Elstow for the purpose of error checking. All back-2 rainfall simulation tests were conducted before seeding, with the exception of the simulation on May 23, 2002 for watershed D, which was conducted after seeding.

During each rainfall simulation test, a bulked surface soil sample (0 – 5 cm depth) was collected within 1 m diameter of rainfall simulations test location, using a small shovel to collect 5 to 10 subsamples.

There were changes in operators and equipment between 1998 and 2002. From 1998 to 2000, the data were collected by various people. However, I joined the project in 2001, and conducted the sampling and rainfall simulations tests of Elstow 2002.

3.2.1 Equipment Set-up for Rainfall Simulation Tests

Simulator

The design of the two rainfall simulators was used in this research and were similar to that of Meyer and Harmon (1979). The first rainfall simulator used to collect baseline information in fall 1998 at Perdue was damaged beyond repair; therefore, a new simulator was built in May 2000. All other rainfall simulation tests in Perdue and Elstow were conducted with the new simulator.

The first simulator had an aluminum frame structure, 3 m in height with a 1.6 m x 2.3 m rain area on the ground (Fig. 3.5). Two oscillating VeeJet nozzles (80100) were set up on the top of the frame structure to apply water. The collecting ground area for runoff was around 1.5 m^2, determined by pushing 1.5 m and 1 m long steel siding 30-50 mm into the ground (Maule and Reed, 1993). Only Perdue 1998 rainfall simulation tests were conducted with the first simulator.

Fig. 3.5: The first rainfall simulator used to collect Perdue baseline data in fall 1998.

The new rainfall simulator has a PVC frame structure 2 m high and a wetting area of 1.5 m x 1.5 m on the ground. Two identical spray nozzles were set up on the top of the simulator to apply water as simulated rainfall (Fig. 3.6).

Fig. 3.6: The new rainfall simulator used in Perdue May 2000 rainfall simulation tests.

Two sizes of FullJet square spray brass nozzles from Spraying System Co. were used at different times with the new simulator to apply water in square/oval full core pattern. Smaller nozzles (product number: 1/8HH-6SQ) were used for Perdue 2000 rainfall simulation tests; large nozzles (product number: 3/8HH-18SQ), which had 3 times higher capacity than the small nozzles, were used for all rainfall simulation tests in Elstow (2000, 2001, 2002). The small nozzles (product number: 1/8HH-6SQ) have the capacity of 1.1 gallons min^{-1} and orifice diameter nom. of 0.094 inches, and their spray angles range from 60 to 66 degrees with the water pressure ranging from 7 to 80 psi. The large nozzles (product number: 3/8HH-18SQ) have a capacity of 3.4 gallons min^{-1} and orifice diameter nom. of 0.156 inches, and their spray angles range from 68 to 75 degrees with the water pressure ranging from 7 to 80 psi. The large nozzles have approximately three times the capacity and a 10-degree larger spraying angle than the small nozzles.

Ground Equipment

Rainfall simulation tests were conducted at locations without new disturbance or obvious compaction. For all rainfall simulation tests, the collecting plot was oriented with the long axis down slope. Two 1 m x 0.15 m metal area side boundaries were pushed several centimeters into the soil with a 0.9 m long metal sheet pushed in between at the top; therefore, the runoff collecting area was 0.9 m^2. A triangular metal tray was pushed into the soil face at the lower slope outlet, several centimeters below the soil surface, to collect runoff. Sampling bottles were placed in a hole (depth of 40 cm) in front of the triangle tray. Two rain gauges were placed (one in the center and the other one at the upper slope boundary of collecting area) to monitor rainfall application rate (Fig. 3.7).

After the ground equipment was installed, the simulator was set up and connected to the water supply via a garden hose. Tarpaulins were fixed to four sides of the frame structure to protect rainfall from wind. To stabilize the simulator on the ground, two to four stakes were hammered into the soil and tied to the legs of the simulator.

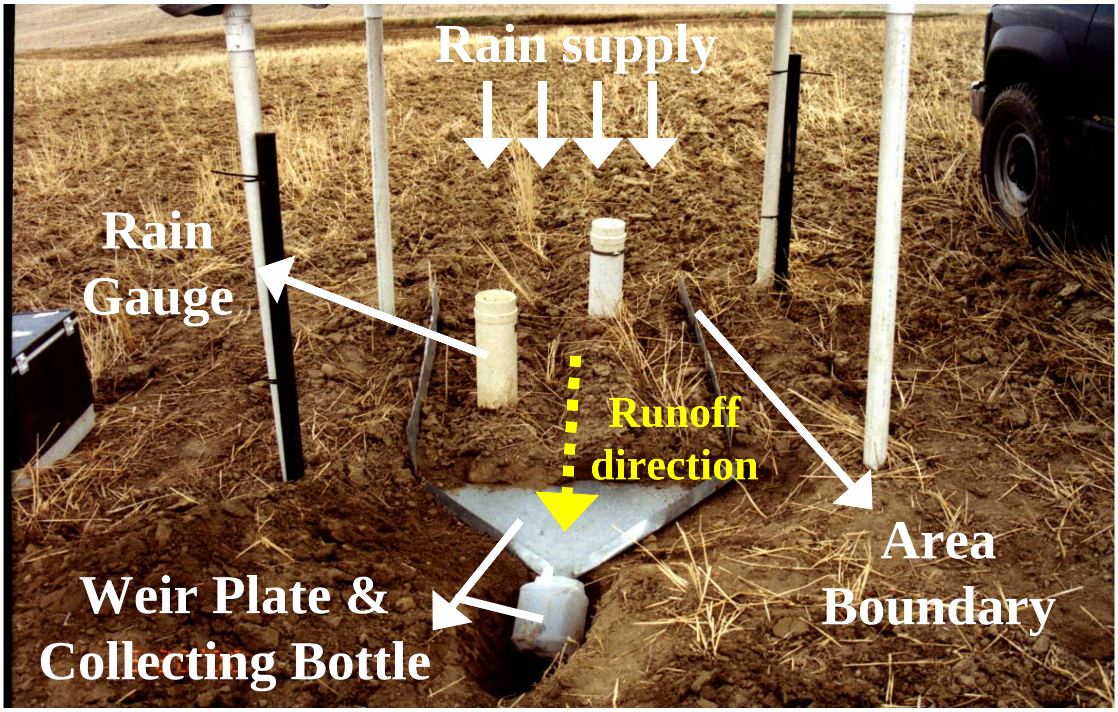


Fig. 3.7: Ground equipment set-up in rainfall simulation at Elstow (spring 2001).

The water sources for rainfall simulation tests at the Perdue site were surface water from a dugout for 1998, and well water from the town of Perdue for 2000. The water source for all rainfall simulation tests at the Elstow site (2000, 2001, and 2002) was well water from the town of Elstow.

Rainfall Intensity

Rainfall intensity was monitored by two rain gauges during each rainfall simulation test, one placed in the center and one near the corner along the upper slope of the runoff collecting area. An average of all rainfall simulation tests from the same year was used to represent rainfall intensity (Table 3.8, Appendices D1 and D2). Perdue 1998 had the lowest intensity, and Elstow 2000 had the highest. Even using the same simulator, larger nozzles were used at Elstow (2000,2001, and 2002) resulting in a rainfall intensity 3 to 5 times higher than that at Perdue for the year 2000 (Table 3.8).

Table 3.8: Rainfall intensity (mm h^{-1}) of rainfall simulation tests.

Site	Year	Average (mm h^{-1})	Standard deviation	Number of measurements
Perdue	1998	33	11	9
	2000	74	69	9
Elstow	2000	388	223	12
	2001	254	90	3
	2002	216	89	20

Note:
- Measurements from rainfall simulation tests are in the respective years for respective sites.
- BEFORE: Perdue 1998; Elstow 2000 and 2001.
- AFTER: Perdue 2000; Elstow 2002.

3.2.2 Rainfall Simulation Test Protocol

Rainfall simulation test protocol and activities are summarized into a flowchart in Fig. 3.8, and the details are addressed in the following sections.

During each rainfall simulation test, water was applied continuously (as simulated rainfall) until runoff had been generated for a pre-determined time (35 minutes for Perdue 1998, 30 minutes for Perdue 2000, and 25 minutes for all Elstow rainfall simulation tests). The time between commencement of rainfall and runoff initiation (i.e. runoff dripping from the collecting tray to a bottle) was recorded as runoff initiation time. Runoff volume was monitored during rainfall simulation tests as soon as runoff started and recorded for each 5-minute interval. Runoff samples were collected at 15 minutes after runoff initiation in all rainfall simulation tests and refrigerated in a cooler at 4 ^{o}C for later chemical and microbial analysis. In rainfall simulation tests at the back slope positions, runoff samples were also taken at 5 and 25 minutes after runoff initiation. For rainfall simulation tests in different years, rain samples were taken at the beginning and at the end of the series, and submitted for the same chemical and microbial analyses as runoff samples. All rainfall simulation tests in the same year were conducted within a three-week period to ensure minimum change in soil conditions occurred with time or weather. In each rainfall simulation test, a soil sample from depth of 0 – 5 cm was collected adjacent to each rainfall simulation test location for analysis of soil nutrient supply rates.

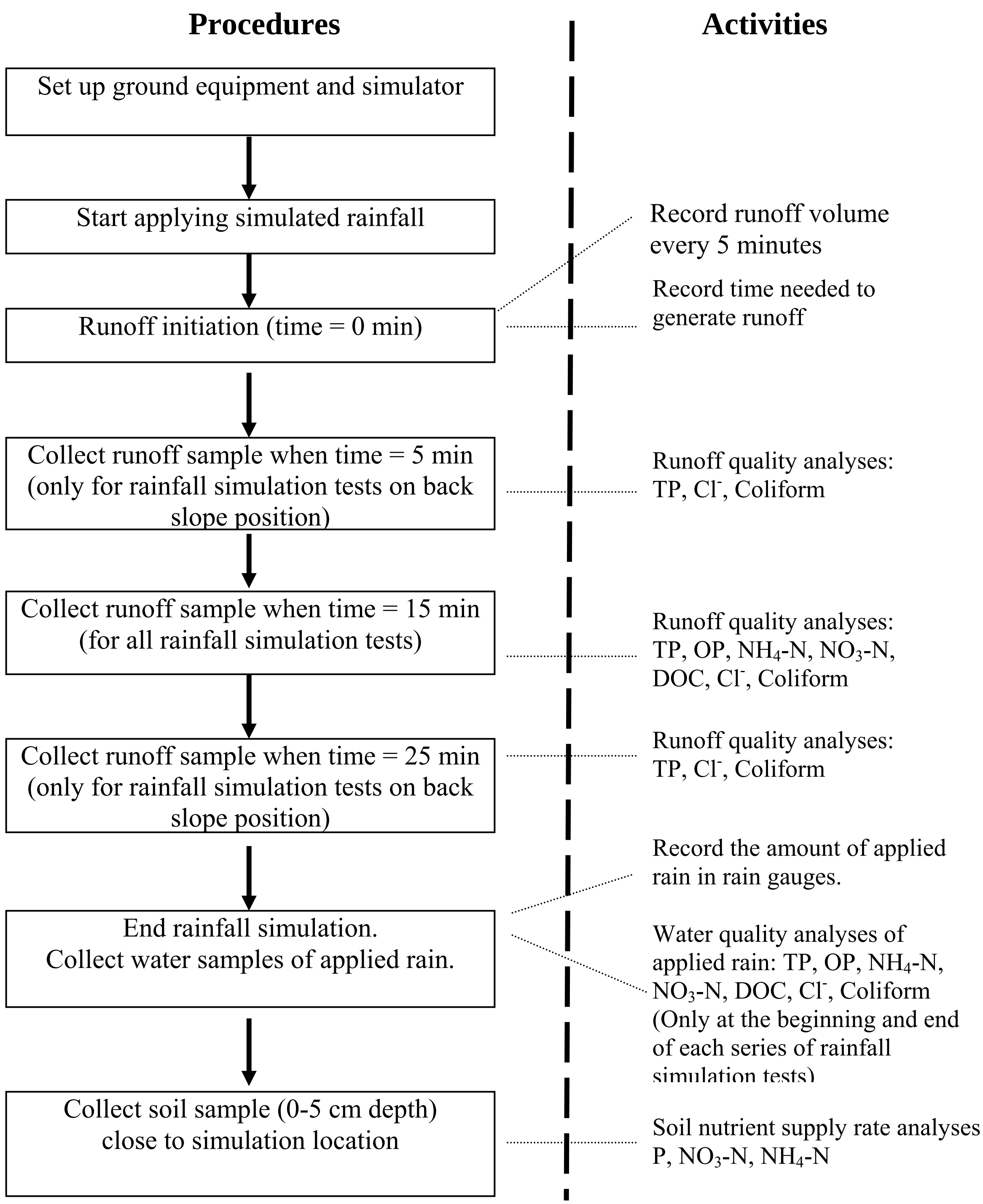


Fig. 3.8: Rainfall simulation test protocol and activities.

3.2.3 Rainfall Uniformity Test

A 20-minute rainfall simulation test was conducted at the shoulder slope position in watershed D of the Elstow site on Oct 7, 2003 using the new simulator with large nozzles. Nine cylinders (1 liter) were placed in a grid located within the runoff collecting area to check the rain application pattern by collecting the simulated rain during rainfall simulation tests. The diameter of each cylinder was 6.5 cm, and rainfall collecting time was 20.3 minutes. The set up is shown in Fig. 3.9.

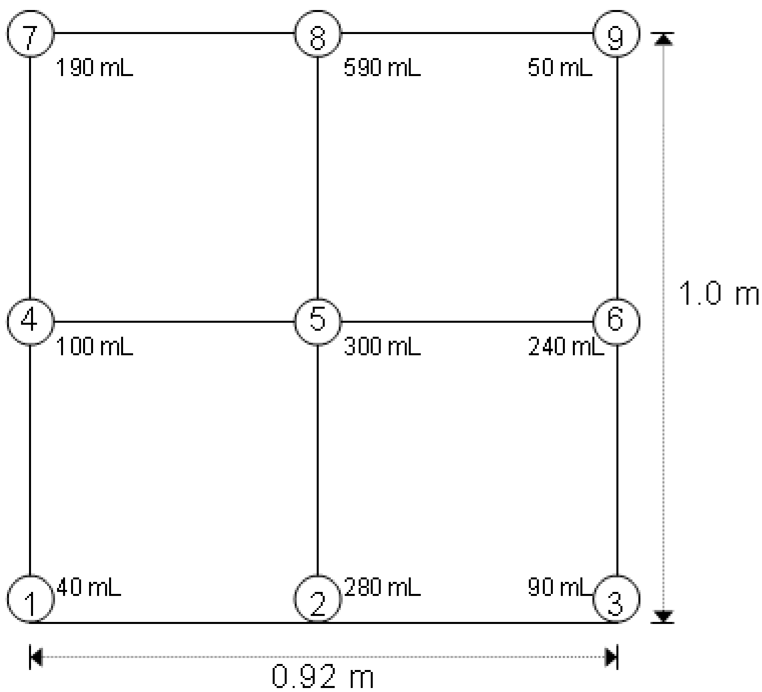
Fig. 3.9: Equipments set-up for the uniformity test.

Figure 3.10 shows the setup and the results of the uniformity test. The numbers in circles are for different cylinders, and the volume collected in each cylinder is specified beside the cylinder number. Numbers 1, 2 and 3 are the front cylinders close to the sampling tray. The average of all volume collections was 209 mL with standard deviation (SD) of 173 ml, and the average rainfall intensity was 227 mm h^{-1} with SD of

172 mm h^{-1}. The highest rainfall intensities were found along the centerline (cylinders number 2, 5, and 8) where one of the rain gauges was usually placed during rainfall simulation tests. Uniformity was calculated according to the following equation:

$$U = 100\% \, (1.0 - V) \qquad \text{[Eq. 3.1]}$$

where U is uniformity and V is the statistical coefficient of variation. The uniformity was 43% for the simulator used for Elstow rainfall simulation tests.



Front (runoff collection)

Note:

- The two nozzles were located right above cylinders number 5 and 8.

Fig. 3.10: Set-up and results of rainfall uniformity test.

3.2.4 Rate Calculation

Rainfall Application Rate (Intensity)

In each rainfall simulation test, applied rainfall was monitored by two rain gauges throughout the whole rainfall simulation test. Rainfall application rate was calculated using Eq. 3.2 below:

$$I = \frac{V_p}{t_p A_p}$$ [Eq. 3.2]

where I is rainfall intensity (L min^{-1} m^{-2} or mm min^{-1}), V_p is the volume of rain collection in a rain gauge (L), A_p is the collection area of rain gauge (m^2)and t_p is rainfall application time (min). The time of rainfall application is the combination of rainfall simulation test time (35 minutes for Perdue 1998, 30 minutes for Perdue 2000, and 25 minutes for all rainfall simulation tests in Elstow) and the time needed to generate runoff (runoff initiation time), which was different for each rainfall simulation test.

Since the calculated rainfall intensity would vary due to the placement of rain gauges and the uneven rainfall pattern, average rainfall intensity was calculated for rainfall simulation tests within the same year by the same equipment (Table 3.8).

Runoff Rate

Runoff volume was collected and recorded at 5-minute intervals and runoff rate was determined using the following equations. For each collection interval, runoff rate was determined from runoff volume, collecting area, and collecting time using Eq. 3.3 and Eq. 3.4, and was assumed to be consistent during the time interval of collection.

$$r = \frac{V}{\Delta t * A}$$ [Eq. 3.3]

where r is the runoff rate during a collecting time interval (L min^{-1} m^{-2} or mm min^{-1}), V is the total runoff volume (L) during a collecting time interval of Δt (min), and A is the runoff collecting ground area (m^2). The runoff collecting ground area was 1.5 m^2 for the Perdue 1998 rainfall simulation tests, and 0.9 m^2 for all other rainfall simulation tests (Perdue 2000; Elstow 2000, 2001, and 2002).

Samples for chemical analyses were collected at 15 minutes after runoff initiation on shoulder and foot slope positions; on back slope position, samples were collected at 5, 15, and 25 minutes after runoff initiation. The volume of samples was recorded and included in the total volume monitored during the 5-minute time intervals.

By assuming a consistent change of runoff rate between two collecting time intervals, the runoff rate during sampling was calculated using Eq. 3.4 with Eq. 3.5 or Eq. 3.6.

$$r_s = \frac{(r_2 - r_1)(t - t_1)}{t_2 - t_1} \qquad \text{[Eq. 3.4]}$$

where t is the representative time of sampling period (min), t_1 is the representative time of one collecting time interval (min), t_2 is the representative time of the next collecting time interval (min), r_s is the runoff rate at t (L min^{-1} m^{-2} or mm min^{-1}), r_1 is the runoff rate at t_1 (L min^{-1} m^{-2} or mm min^{-1}), and r_2 is the runoff rate at t_2 (L min^{-1} m^{-2} or mm min^{-1}).

The representative time of sampling period was calculated differently in different sampling periods. For sampling at 5 and 15 minutes after runoff initiation, the representative time is calculated using Eq. 3.5:

$$t = \frac{V_s}{V} * \Delta t * \frac{1}{2} + t_1 \qquad \text{[Eq. 3.5]}$$

where V_s is the volume of samples (L), and all other variables are as defined in previous equations.

There was no runoff volume monitoring after 25 minutes of runoff initiation. Therefore, the sampling at 25 minutes after runoff initiation was calculated based on the assumption of a consistent change of runoff rate during the collecting interval prior to sampling. For sampling at 25 minutes after runoff initiation, the representative time is calculated using Eq. 3.6:

$$t = \frac{V_s}{V} * \Delta t * \frac{1}{2} + t_2 \qquad \text{[Eq. 3.6]}$$

Examples of runoff rate calculation can be found in Appendix E.

Chemical Loading Rate

Chemical loading rate is determined by chemical concentrations in runoff and rain, and the runoff rate using Eq. 3.7:

$$L = (M - M_w) * r_s \qquad \text{[Eq. 3.7]}$$

where L is the chemical loading rate (mg min^{-1} m^{-2}), M is the chemical concentration of runoff samples (mg L^{-1}), M_w is the chemical concentration of water used for rainfall simulation tests (mg L^{-1}), r_s is the runoff rate during sampling as defined in Eq. 3.4 (L min^{-1} m^{-2} or mm min^{-1}). M_w is the average chemical concentration of several samples of water used for rainfall simulation tests within the same year by the same equipment.

3.2.5 Visual Observations

Several observations of rainfall simulation tests in the field are addressed as below.

1. On windy days, soil loading in runoff water samples was somewhat higher. Possible reason could be that wind blew soil onto the collecting weir plate and runoff carried it into the sampling bottles. However, the record of wind speed was not available for all rainfall simulation tests. Therefore, this can only be a possible hidden effect of weather on runoff chemistry.

2. Several rainfall simulation tests had water running under the weir plate. This would result in loss of runoff water volume if water was lost from the collecting area. The water could also have come from infiltrated lateral water flow or simply from outside of the collecting area.

3. Rainfall simulation tests in BEFORE and AFTER for Perdue and Elstow were conducted by various operators in different years. Some variation of rainfall simulator set-up and sampling procedures between different operators could be expected.

3.3 Physical and Chemical Analyses

The timelines of sample collections and methods of all sample analyses are summarized in Table 3.9.

Table 3.9: Methods and timelines for tests and sampling.

Sample	Sampling Date	Analytical Parameter	Analysis Technique and Source
Soil (0-15 cm)	Perdue: fall 1998 Elstow: fall 2001	Soil texture	Modified pipette method (Indorante et al., 1990)
Soil (0-5 cm)	Perdue: fall 1998, spring 2000. Elstow: fall 2000 and 2001, spring 2002.	Soil nutrient supply rates: PO_4-P, NO_3-N, NH_4-N, and ions.	Plant Root Simulator probes (Qian and Schoenau, 2002)
Liquid hog manure	Perdue: fall 1999 Elstow: fall 2001	NO_3-N and NH_4-N	Colorimetrical method, Technicon Autoanalyzer II
		SO_4-S and PO_4-P	Anion exchange resin membranes, Technicon Autoanalyzer II (Schoenau and Huang, 1991)
		The percent total C, N, and S	LECO CNS 2000 combustion analyzer
		P, Ca, Mg, K, Fe, Mn, Cu, Zn, B, Cd, and Pb	Inductively coupled plasma emission spectroscopy, Perkin Elmer Optima 3000 DV
Runoff and water source samples from rainfall simulation tests	Perdue: fall 1998, spring 2000. Elstow: fall 2000 and 2001, spring 2002.	OP	Reduction using stannous chloride (Environment Canada, 1979a)
		TP	Reduction using stannous chloride with pre-treatment (Environment Canada, 1979a)
		NO_2-NO_3 (shown as NO_3-N)	Automated cadmium reduction method (Clesceri et al., 1989)
		NH_4-N	Hypochlorite and alkaline phenol method with pre-stabilization (Skougstad et al., 1979)
		DOC	Persulphate UV oxidation method
		Cl^-	Standard chloride meter (ion selective electrode)
		Coliform	IDEXX Technical Bulletin Method (Patent #'s 4 925 789, 5 429 933, and 5 518 892).

3.3.1 Soil Texture and Nutrient Supply Rates

Soil samples of 0 – 15 cm depth were collected from different slope positions of all watersheds for soil texture determination. A modified pipette procedure was used to determine the clay and sand content of soil samples (Indorante et al., 1990).

Soil samples of 0 – 5 cm of depth were collected within 1 m of each rainfall simulation test location for determination of soil nutrient supply rates in the surface soil, to estimate the nutrients potentially available for transport in runoff. Soil nutrient supply rates, including ammonium, nitrate and phosphate ions, were determined using Plant Root Simulator probes, which has been used in almost 400 publications of soil and environmental studies as reported in the review paper by Qian and Schoenau (2002). These probes use synthetic ion exchange resins to examine ion bioavailability in soil and sediment. In this method, an anion exchange membrane encapsulated in a plastic probe is inserted into the soil sample. Ions in the soil then exchange with ions on the membrane and accumulate on the surface of the membrane probe over time. After 24 hours, the probe is removed from the soil and the sorbed ions are eluted with HCl. The ion concentration in the HCl is then determined using inductively coupled plasma emission spectroscopy.

3.3.2 Hog Manure Chemistry

A sub-sample of manure was digested in a H_2SO_4-H_2O_2 digestion (Thomas et al., 1967), and then analyzed for P, Ca, Mg, K, Fe, Mn, Cu, Zn, B, Cd, and Pb using inductively coupled plasma emission spectroscopy (Perkin Elmer Optima 3000 DV). Undigested manure samples were used to determine soluble NO_3-N and NH_4-N colorimetrically using the Technicon Autoanalyzer II. The soluble SO_4-S and PO_4-P in undigested manure samples were determined using anion exchange resin membranes and Technicon Autoanalyzer II. The method for available-P analysis in the manure was a modified method developed by Schoenau and Huang (1991) using anion exchange resin membranes. The percent total C, N, and S in manure samples (wet weight basis) were analyzed using a LECO CNS 2000 combustion analyzer (Charles, 1999).

3.3.3 Water Chemistry

Runoff and water source samples were analyzed for total phosphorus (TP), ortho phosphorus (OP), nitrite-nitrate (NO_3-N), ammonium (NH_4-N), and dissolved organic carbon (DOC) by the Regional Water Quality Laboratory of Environment Canada using standard colorimetric methods. TP and NH_4-N were determined on unfiltered samples but aliquots for NO_3-N and OP were filtered through a Whatman glass microfibre filter that had been baked for 4 h at 525 ^oC. Phosphorus was measured as OP by reduction using stannous chloride (Environment Canada, 1979a). For the determination of TP, the aliquot was treated with a sulphuric acid - persulphate mixture to release organically bound phosphates and hydrolyze polyphosphates to OP prior to reduction (Environment Canada, 1979b). The automated cadmium reduction method described by Clesceri et al. (1989) was used to determine NO_3-N. Sulphuric acid was used to stabilize an aliquot prior to NH_4-N determination by reaction with hypochlorite and alkaline phenol (Skougstad et al., 1979). Water samples for DOC were acidified and spurged to remove inorganic C; organic C was analyzed using the persulphate UV oxidation method; the resulting CO_2 was measured with a non-dispersive IR detector in a Phoenix 8000 TOC analyzer (Environment Canada, 2002). Chloride analysis was completed by a standard chloride meter with ion selective probe (ORION).

Runoff and water source samples were also submitted to the Saskatchewan Research Council Analytical Laboratory for fecal coliform analysis using the IDEXX Technical Bulletin Method (Patent #'s 4 925 789, 5 429 933, and 5 518 892). All water samples were submitted within 24 hours of collection. The samples were stored at 4 ^oC until analysis.

3.4 Statistical Analyses

A paired two-tailed t-test was performed using Microsoft Excel (Office 2000) to determine the significance (α=0.10) of differences between data before and after manure application. The significance of differences between data from control and manured watersheds was determined by two-tailed t-tests (α=0.10) with F-test (α=0.10) results, used to determine the type of t-test (equal or unequal variance). Differences in data between watersheds were tested using Fisher's protected LSD (Steel and Torrie, 1980) where the LSD (α=0.10) is only performed using SAS when a significant F value (α=0.10) is obtained in the analysis of variance.

4. RESULTS

4.1 Soil Characteristics and Manure Chemistry

4.1.1 Soil Characteristics

Perdue

The texture of 0 – 15 cm depth soil in watershed A is generally silt loam, whereas soils in watershed B range from loam to silt loam, and watershed C is a silt loam to silt clay loam soils (Table 4.1, Appendix E). Soils were not pretreated for organic matter removal.

Table 4.1: Soil characteristics – Perdue.

Watershed	Slope position	Slope %	Clay %	Sand %	Texture
A	shoulder	7.4	20	12	SiL
	back	9.6	15	18	SiL
	foot	7.4	16	20	SiL
B	shoulder	3.9	21	33	L
	back	7.4	20	44	L
	foot	3.7	13	36	SiL
C	shoulder	3.9	32	20	SiCL
	back	11.3	25	28	L
	foot	9.9	19	28	SiCL

Note:
- All soil samples were collected at 0 – 15 cm depth of soil near the locations of rainfall simulation tests.
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.

Elstow

The texture of 0 – 15 cm of soil is silt loam for watersheds A, B, and E. In watershed C, soils range from a silt loam to a silt clay loam. The soils in watershed D range from a loam to a silt loam (Table 4.2, Appendix E). These textures are similar to those at Perdue, but soils at Perdue show a greater texture variation from shoulder to foot slope positions (Table 4.1).

Table 4.2: Soil characteristics – Elstow

Watershed	Slope position	Slope %	Clay %	Sand %	Texture
A	shoulder	2.0	6	32	SiL
	back	6.9	19	29	SiL
	foot	5.8	14	28	SiL
B	shoulder	3.5	26	11	SiL
	back	3.0	16	20	SiL
	foot	1.5	16	17	SiL
C	shoulder	0.0	25	14	SiL
	back	2.5	18	19	SiL
	foot	3.7	33	17	SiCL
D	shoulder	3.2	19	30	SiL
	back	3.9	20	28	SiL
	foot	5.4	21	32	L
E	shoulder	0.0	18	28	SiL
	back	1.2	17	25	SiL
	foot	2.2	16	23	SiL

Note:

- All soil samples were collected at 0 – 15 cm depth of soil near the locations of rainfall simulation tests.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 $m^3\ ha^{-1}$, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

4.1.2 Manure Chemistry

Perdue

During manure application, samples were taken in duplicate from the manure injection tank when the tank was full and almost empty, and then analyzed for their chemical properties. The results of the chemical analysis of manure are summarized in Table 4.3, and more parameters can be found in Appendix F1.

Table 4.3: Manure chemical concentrations (mg L^{-1}) – Perdue.

Concentration mg L^{-1}	TN	TP	K	NH_4-N	OP	Cl^-
Average (SD)	2766 (96)	690 (260)	1416 (20)	1889 (208)	72 (26)	753 (194)

Note:
- OP: orthophosphate
- Values in '()' are the standard deviations (SD).
- Average values are from 4 samples.

Elstow

Manure applied on watersheds B and E was sampled at the beginning and end of each day, whereas manure applied to watersheds D and C was sampled near the beginning and end of the application. The results of the chemical analysis of manure are summarized in Table 4.4, and more parameters can be found in Appendix F2.

Table 4.4: Manure chemical concentrations (mg L^{-1}) – Elstow.

Concentration mg L^{-1}	TN	TP	K	NH_4-N	OP	Cl^-
Average (SD)	4954 (794)	582 (319)	1892 (321)	3626 (603)	182 (24)	157 (22)

Note:
- OP: orthophosphate
- Values in '()' are the standard deviations (SD).
- Average values are from 12 samples.

4.2 Rainfall Simulation Tests – Perdue

In the following sections regarding the Perdue site, 'BEFORE' refers to rainfall simulation tests conducted before manure addition (fall 1998), and 'AFTER' refers to those conducted after manure addition (spring 2000). Manure was added in fall of 1999. One simulation was conducted in each slope position (shoulder, back, and foot) at all three watersheds (A, B, and C) for BEFORE and for AFTER (Table 3.7).

4.2.1 Water Quality of Simulated Rainfall

The water used in rainfall simulation tests was sampled and analyzed for the same chemical parameters as those for runoff. The water source for BEFORE was surface water from a dugout, whereas for AFTER the water source was ground water from a local well. The average water chemistry of the simulated rainfall in AFTER had higher NO_3-N (by about an order of magnitude) and Cl^- concentrations than those in BEFORE (Table 4.5, Appendix G1).

Table 4.5: Chemistry (Δ conc.) of water used in rainfall simulation tests – Perdue

	Rain sample #	TP	OP	NH4-N	NO3-N	DOC	Cl^-	Coliform
		mg L^{-1}						ct $100mL^{-1}$
BEFORE	1	0.044	0.006	0.181	0.028	2.4	3.3	24200
	2	0.020	0.002	0.184	0.034	2.4	3.5	13500
	3	0.013	0.002	0.155	0.036	5.5	3.2	3300
	4	0.012	0.002	0.187	0.038	2.5	3.2	359
	5	0.014	0.002	0.138	0.064	2.5	3.3	3
	Average	0.021	0.003	0.169	0.040	3.1	3.3	8272
	SD	0.013	0.002	0.022	0.014	1.4	0.1	10449
AFTER	Rain#1	0.006	0.003	0.479	0.695	4.3	29.1	<1
	Rain#2	0.006	0.005	0.396	2.310	5.4	33.3	<1
	Average	0.006	0.004	0.438	1.503	4.9	31.2	<1
	Range	0.000	0.002	0.083	1.615	1.1	4.2	<1

Note:
- 'BEFORE' refers to rainfall simulation tests conducted before manure addition (1998); 'AFTER' refers to those conducted after manure addition (2000).
- 'SD' refers to standard deviation, and 'Range' is the difference between maximum and minimum.
- Coliform tests: total coliform for BEFORE; fecal coliform for AFTER.

4.2.2 Runoff Initiation Time and Runoff Rate during Sampling

The average time to generate runoff was 8.8 (SD of 7.7) minutes for BEFORE, and 16.7 (SD of 12.8) minutes for AFTER (Table 4.6). For AFTER, more time was generally required to generate runoff at the foot slope positions than at other landscape positions. There were no significant differences (t-test, α=0.10) in the runoff initiation time between BEFORE and AFTER (Table 4.6).

Table 4.6: Runoff initiation time (min) – Perdue.

Watershed	Slope position	BEFORE (min)	AFTER (min)
A	shoulder	1.5	15.3
	back	3.0	7.5
	foot	7.0	21.6
B	shoulder	26.0	1.7
	back	10.1	9.5
	foot	14.8	16.2
C	shoulder	9.7	8.1
	back	4.1	25.6
	foot	3.0	44.6

Note:
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.
- 'BEFORE' refers to rainfall simulation tests conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000).

The runoff rate during sampling is calculated according to Eq. 3.4 with Eq. 3.5 or Eq. 3.6, and the results are summarized in Table 4.7 (Appendix H1). On all slope positions (i.e. shoulder, back, foot), runoff samples were taken at 15 minutes after runoff initiation. The average runoff rates during sampling at 15 minutes after runoff initiation were 0.56 (SD of 0.40) mm min^{-1} m^{-2} for BEFORE, and 0.16 (SD of 0.04) mm min^{-1} m^{-2} for AFTER. Runoff rates during sampling at 15 minutes were significantly different (t-test, α=0.10) between BEFORE and AFTER, with BEFORE being about three times greater than AFTER. For both BEFORE and AFTER, the highest 15-minute runoff rates occurred on the back slope position in all watersheds, except watershed C in AFTER (Table 4.7).

Only on the back slope positions were runoff samples taken at three times (at 5, 15, and 25 minutes after runoff initiation), and therefore the data from back slope positions were used to assess the temporal change in runoff rate. For both BEFORE and AFTER, runoff rates during sampling were lowest at 5 minutes after runoff initiation in all watersheds, with the exception of watershed B in BEFORE (Table 4.8).

Table 4.7: Runoff rate (mm min^{-1} m^{-2}) during sampling at 15 minutes after runoff initiation – Perdue

Watershed	Slope position	BEFORE (mm min^{-1} m^{-2})	AFTER (mm min^{-1} m^{-2})
A	shoulder	0.39	0.17
	back	0.57	0.24
	foot	0.41	0.15
B	shoulder	0.21	0.12
	back	1.28	0.20
	foot	0.03	0.17
C	shoulder	0.82	0.18
	back	0.96	0.13
	foot	0.33	0.09

Note:
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.
- 'BEFORE' refers to rainfall simulation tests conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000).

Table 4.8: Temporal runoff rate (mm min^{-1} m^{-2}) during sampling – Back slope positions of Perdue

Watershed	Sampling time (min)	BEFORE (mm min^{-1} m^{-2})	AFTER (mm min^{-1} m^{-2})
A	5	0.46	0.14
	15	0.57	0.24
	25	0.54	0.36
B	5	0.11	0.17
	15	1.28	0.20
	25	0.06	0.33
C	5	0.66	0.08
	15	0.96	0.13
	25	1.23	0.17

Note:
- Sampling time: the time after runoff initiation.
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.
- 'BEFORE' refers to rainfall simulation tests conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000).

4.2.3 Runoff Water Quality

The runoff samples collected from rainfall simulation tests were submitted for coliform tests and chemical analyses. In this section, results from runoff samples collected at 15 minutes after runoff initiation were used to represent the runoff water quality of each simulation.

Coliforms

Runoff samples for the coliform tests were collected only at back slope positions of each watershed. Those runoff samples collected in BEFORE were submitted to total coliforms tests, and those collected in AFTER were analyzed for fecal coliforms. Due to the limit of sample size (only one measurement from each watershed) and different types of coliform test, statistical analysis between watersheds or between BEFORE and AFTER was not possible. Therefore, only visual observations were addressed.

For both BEFORE and AFTER, the average coliform concentration of runoff samples from the three watersheds (Table 4.9) was much higher than that of simulated rain (Table 4.5), by about two orders of magnitude. Despite no manure was ever applied to watershed A, watershed A had the highest count for coliform than watersheds B and C both in BEFORE and in AFTER.

Table 4.9: Coliform concentrations (ct 100 mL^{-1}) of runoff samples (collected at 15 minutes after runoff initiation) from rainfall simulation tests – Perdue.

Watershed	BEFORE	AFTER
	Total Coliform (ct 100mL^{-1})	Fecal Coliform (ct 100mL^{-1})
A	1700000	249
B	34500	17
C	17900	127
Average	584133	131
SD	966404	116

Note:

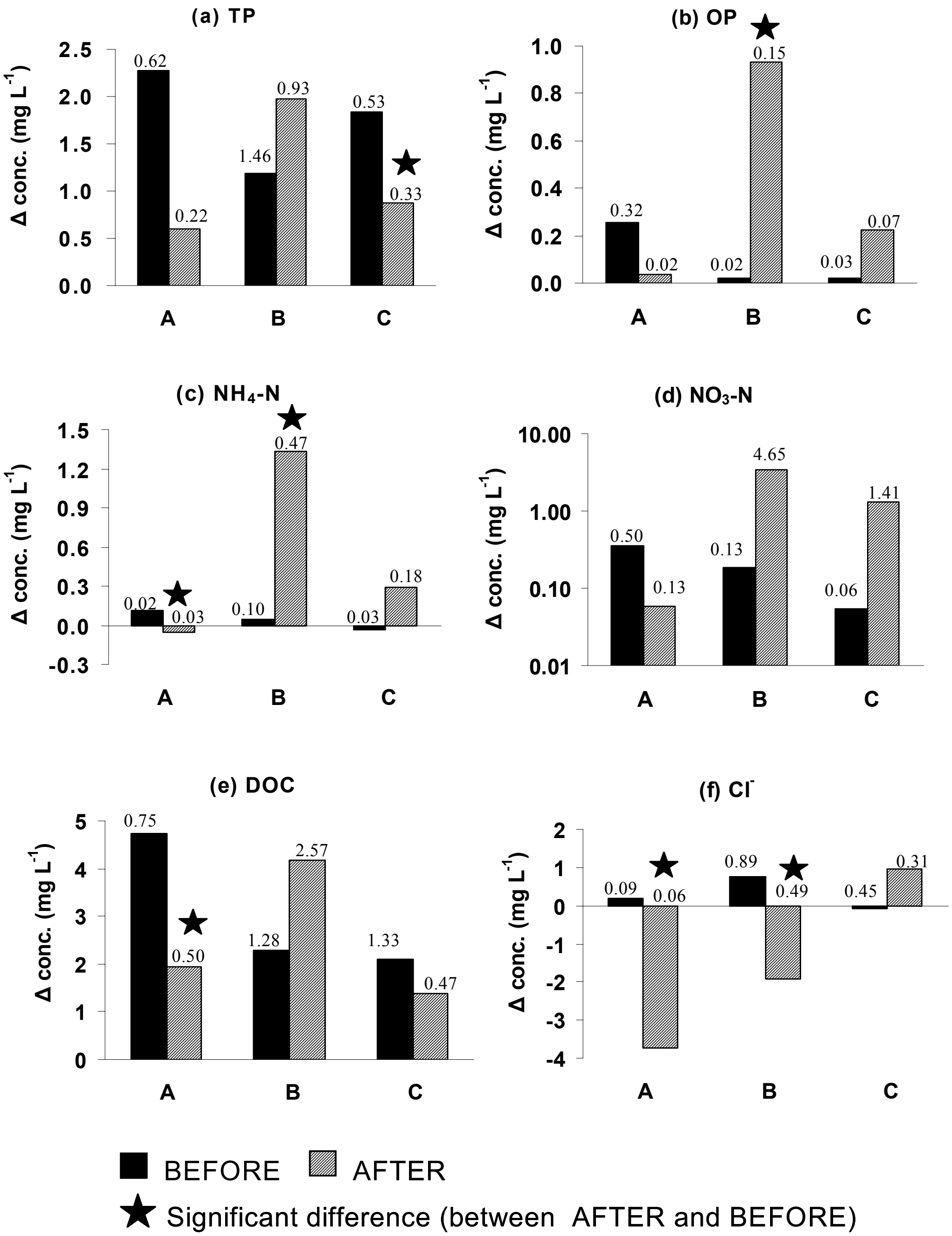
- 'BEFORE' refers to rainfall simulation tests conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000).
- SD: standard deviation
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.

Chemistry

The runoff samples collected from rainfall simulation tests were submitted for chemical analyses for TP, OP, NH_4-N, NO_3-N, DOC, and Cl^-. When comparing runoff chemistry data between BEFORE and AFTER, the background chemistry of the simulated rain (Table 4.5) was subtracted. Due to the wide ranges of simulated rain chemistry in AFTER, Rain#1 was used as background chemistry for rainfall simulation tests conducted on May 16 and 17, 2000, and Rain#2 was used for those on May 18 and 19, 2000 (Appendix G1). Delta concentration (Δ conc. = original runoff chemistry – simulated rain chemistry) is used to present the independent differences in chemical concentrations between runoff and the simulated rainfall, and the original runoff chemical concentrations can be found in Appendix G1. Figure 4.1 shows the average runoff chemistry results of rainfall simulation tests for the different manure treatments independent of rain source. Each value for BEFORE and for AFTER is the average of rainfall simulation tests on the three slope positions (shoulder, back, and foot) within the same watershed. The negative values might be due to the analytical and instrumental errors (for Cl^-) or the great variation in the chemistry of the water used for rainfall simulation tests (for all other parameters).

When assessing the effects of manure on the watersheds it is important to also consider what occurred within the control watershed. The control watershed (A) received only the landowner's chemical fertilizer treatment; whereas watersheds B and C each received different manure treatments along with chemical fertilizer (Table 3.2).

In the control watershed (A), significant differences between BEFORE and AFTER (t-test, α=0.10) were found in delta concentrations (Δ conc.) of NH_4-N, DOC, and Cl^-, with AFTER having lower averages than BEFORE. In watershed B, significant differences appeared in OP, NH_4-N, and Cl^-, with AFTER having higher OP and NH_4-N averages, and a lower Cl^- average. Watershed C had the only significant difference in TP concentration, with AFTER having the lower average (Fig. 4.1).



Note:

- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.
- 'BEFORE' refers to rainfall simulation test conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000). 'Significant difference' is the result of two-tailed t-tests at α=0.10.
- The number above each bar is its standard deviation.
- Δ conc. = Δ concentration = runoff chemical concentration – simulated rain chemical concentration
- Values are averages of 15-minute data from the simulation tests at shoulder, back, and foot slope positions (one measurement from each test) in the same watersheds.

Fig. 4.1: Runoff chemistry (Δ conc.) – Average of three slope positions – Perdue.

When grouping watersheds B and C together as manured watersheds, there were no significant differences (t-test, α=0.10) between BEFORE and AFTER for delta concentrations (Δ conc.) of TP, NO_3-N, DOC, and Cl^-; however, significant differences appeared in OP and NH_4-N, with AFTER having higher average concentrations than BEFORE (Appendix G1).

Fisher's protected LSD (α=0.10) was used to test the significance of differences in delta concentrations (Δ conc.) of runoff chemical parameters between all three watersheds (Table 4.10). In BEFORE, significant differences in runoff chemistry between watersheds appeared for NH_4-N and DOC, with watershed A having significantly greater concentrations than B and/or C. In AFTER, watersheds A and C were statistically similar but were different from B in TP and NH_4-N, with watershed B having significantly greater concentrations than A and C. Despite the greater rate of manure application on watershed C (112 m^3 ha^{-1}), Watershed B (79 m^3 ha^{-1}) had greater concentrations of runoff nutrients for all chemical parameters except Cl^- in AFTER (Fig 4.1, Table 4.10).

Table 4.10: Fisher's protected LSD test results (α=0.10) of runoff chemistry (Δ conc.) between watersheds – Perdue.

	Watershed	TP	OP	NH_4-N	NO_3-N	DOC	Cl^-
BEFORE	A	a	a	a	a	a	a
	B	a	a	ab	a	b	a
	C	a	a	b	a	b	a
AFTER	A	b	c	b	a	a	c
	B	a	a	a	a	a	b
	C	b	b	b	a	a	a

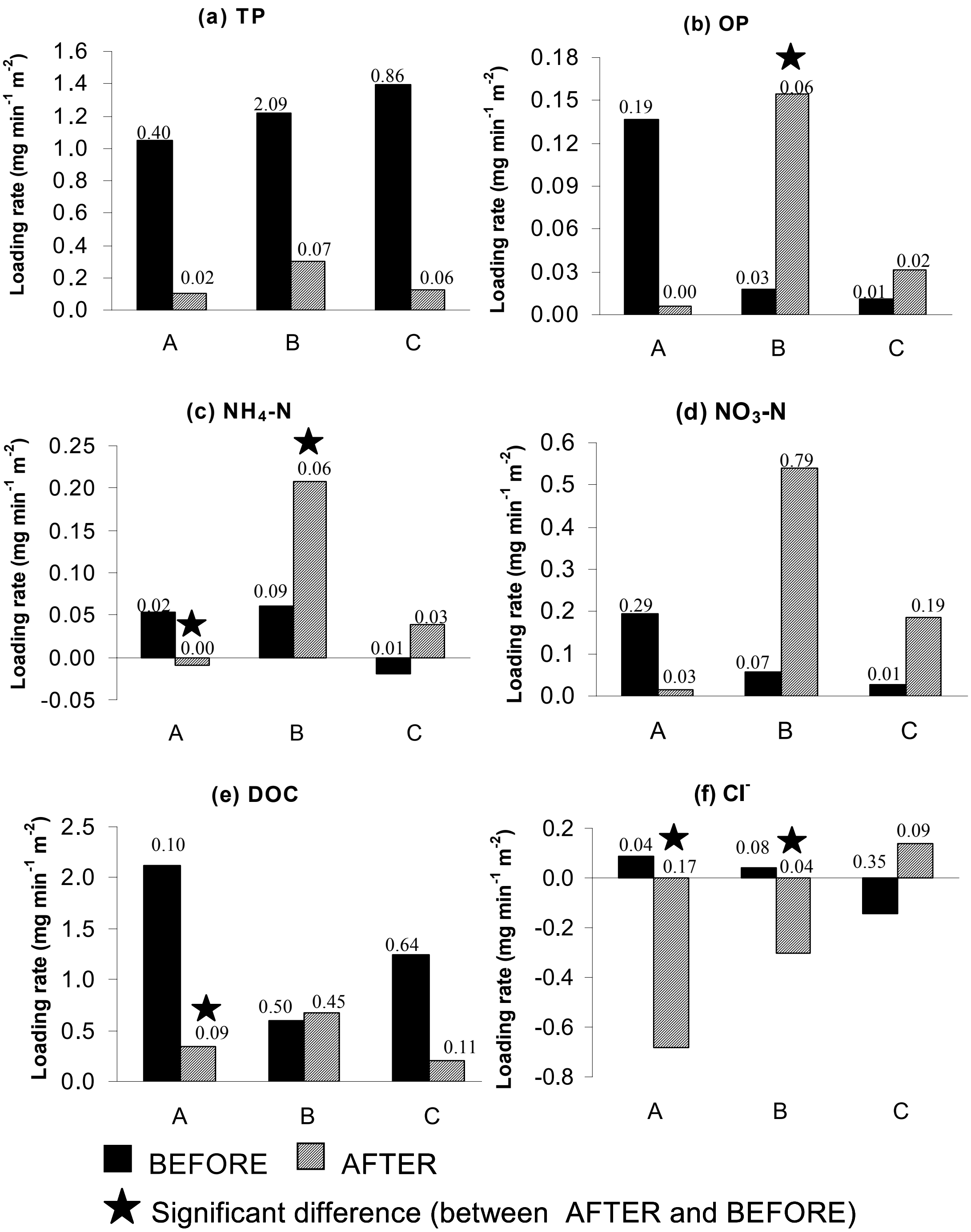
Note:
- 'BEFORE' refers to rainfall simulation tests conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000).
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.
- Different symbols indicate significant difference (α=0.10) amongst watersheds (i.e. "a" is for the higher value; "b" is for the lower value). The same symbol indicates no significant differences between watersheds.
- There were three measurements for each watershed.

Chemical loading rates were calculated using Eq. 3.7. The average chemical loading rates of all slope positions within the same watershed are shown in Fig. 4.2. A paired two-tailed t-test was used to test the significance (α=0.10) of differences between

BEFORE and AFTER. In the control watershed (A), significant differences were found in loading rates of NH_4-N, DOC, and Cl^-, with AFTER having lower averages. In watershed B, BEFORE and AFTER were significantly different in Cl^- loading rate (with AFTER having a lower average), and in OP and NH_4-N loading rates (with AFTER having higher averages). Watershed C showed no significant differences between BEFORE and AFTER in all parameters (Fig. 4.2).

When comparing Fig. 4.1 to 4.2, similar patterns were found in most chemical parameters of AFTER, indicating that the lower runoff rates of AFTER (Table 4.7) did not mask the chemical concentration in the calculation of chemical loading rate (Eq. 3.7), despite the rain application rate being twice as great in AFTER. However, the same consistency was not found for all chemical parameters in BEFORE. This indicated that the runoff rates of BEFORE (Table 4.7), where three times greater than AFTER, had changed the patterns of loading rate from those of concentration during the calculations, which implied a possible influence of the runoff rate on chemical loading rate in BEFORE.

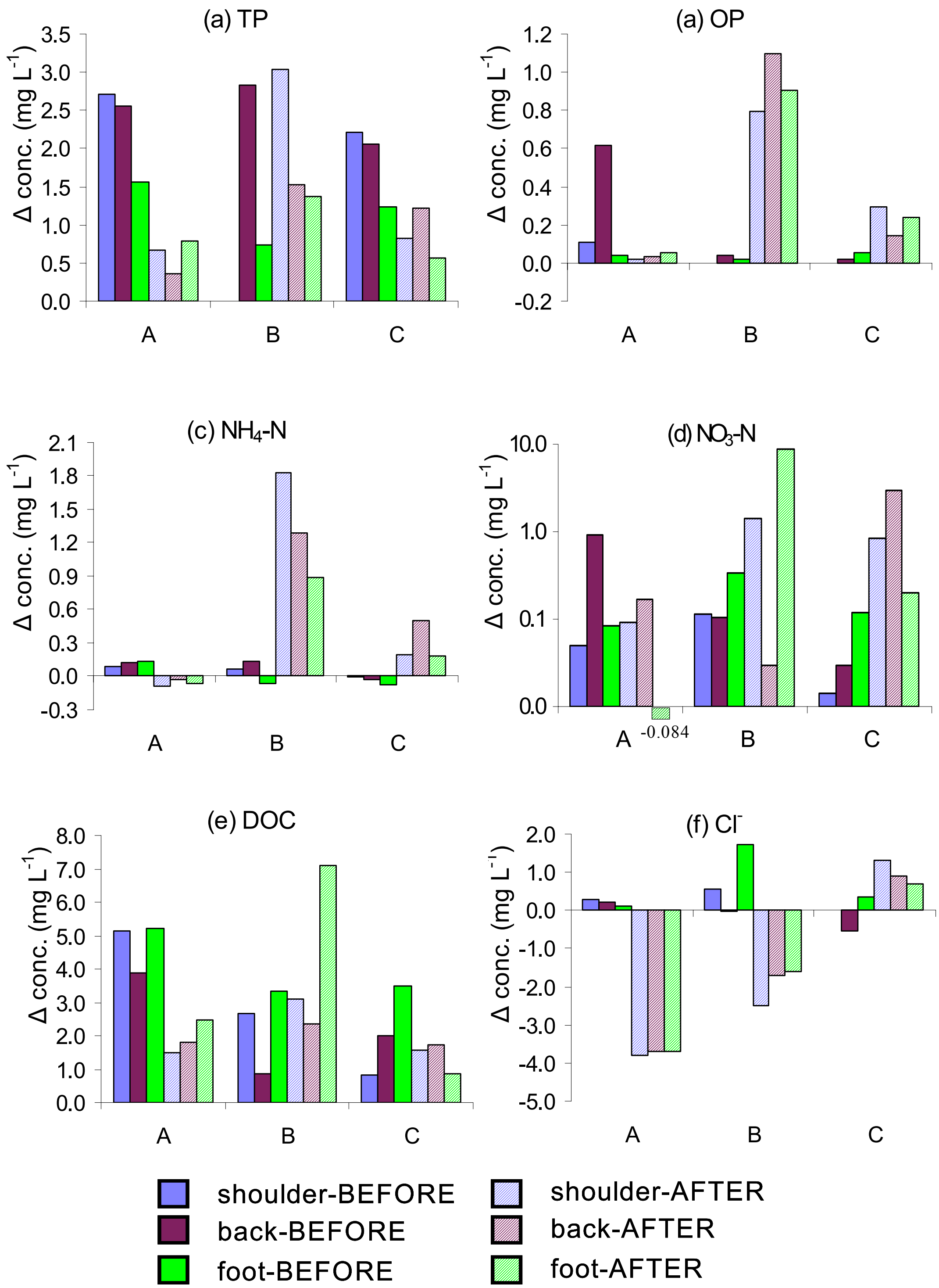
The chemical results of rainfall simulation tests conducted at all three slope positions (shoulder, back, and foot) from all three watersheds for BEFORE and AFTER are shown in Fig. 4.3 (Appendix G1). Similar to Fig. 4.1, delta concentration (Δ conc.) was used on the Y-axis in Fig. 4.3. No overall consistent trend of chemical concentration could be detected via visual comparisons regarding to slope positions in all properties for all watersheds.



Note:

- 'BEFORE' refers to rainfall simulation test conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000). 'Significant difference' is the result of two-tailed t-tests at α=0.10.
- Values are averages of 15-minute data from the simulation tests at shoulder, back, and foot slope positions (one measurement from each slope position) in the same watersheds.
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.
- The number above each bar is its standard deviation.

Fig. 4.2: Runoff chemical loading rate (mg min^{-1} m^{-2}) – Average of three slope positions – Perdue.



Note:

- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 $m^3\ ha^{-1}$, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.
- 'BEFORE' refers to rainfall simulation test conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000).
- The number beneath the bar is its negative value of Δ concentration.
- Δ conc. = Δ concentration = runoff chemical concentration – simulated rain chemical concentration

Fig. 4.3: Runoff chemistry (Δ conc.) – Three slope positions – Perdue.

4.2.4 Temporal Runoff Water Quality

The runoff samples collected at 5, 15, and 25 minutes after runoff initiation were used to analyze the relation of the chemical and coliform concentrations to time. Only rainfall simulation tests at the back slope positions had complete collections at these times for TP, Cl^-, and coliforms.

Coliforms

Runoff samples for the coliform tests were collected only at back slope positions of each watershed. Those runoff samples collected in BEFORE were submitted to total coliforms tests, and those collected in AFTER were analyzed for fecal coliforms. Due to the change of testing coliform types, statistical analysis between watersheds or between BEFORE and AFTER was not reasonable. Therefore, only visual observations were addressed.

For both BEFORE and AFTER, the average coliform concentration of runoff samples from all three watersheds (Table 4.11) was much higher than that of simulated rain (Table 4.5), by about two orders of magnitude; also coliforms were lowest at 15 minutes except on watershed A. For BEFORE, runoff collected at 5 minutes after initiation always had the highest total coliform concentrations. For AFTER, watersheds A and B had the highest fecal coliform concentrations in runoff collected at 25 minutes after initiation; however, watershed C had the highest concentration for the data at 5 minutes after runoff initiation.

Table 4.11: Temporal coliform concentrations (ct 100 mL^{-1}) of runoff from rainfall simulation tests – Back slope positions at Perdue.

Watershed	Sampling time (min)	BEFORE Total Coliform (ct 100mL^{-1})	AFTER Fecal Coliform (ct 100mL^{-1})
A	5	3650000	20
	15	1700000	249
	25	548000	2160
B	5	548000	35
	15	34500	17
	25	116000	285
C	5	34500	2040
	15	17200	127
	25	17900	151
Average		740678	565
SD		1219228	876

Note:

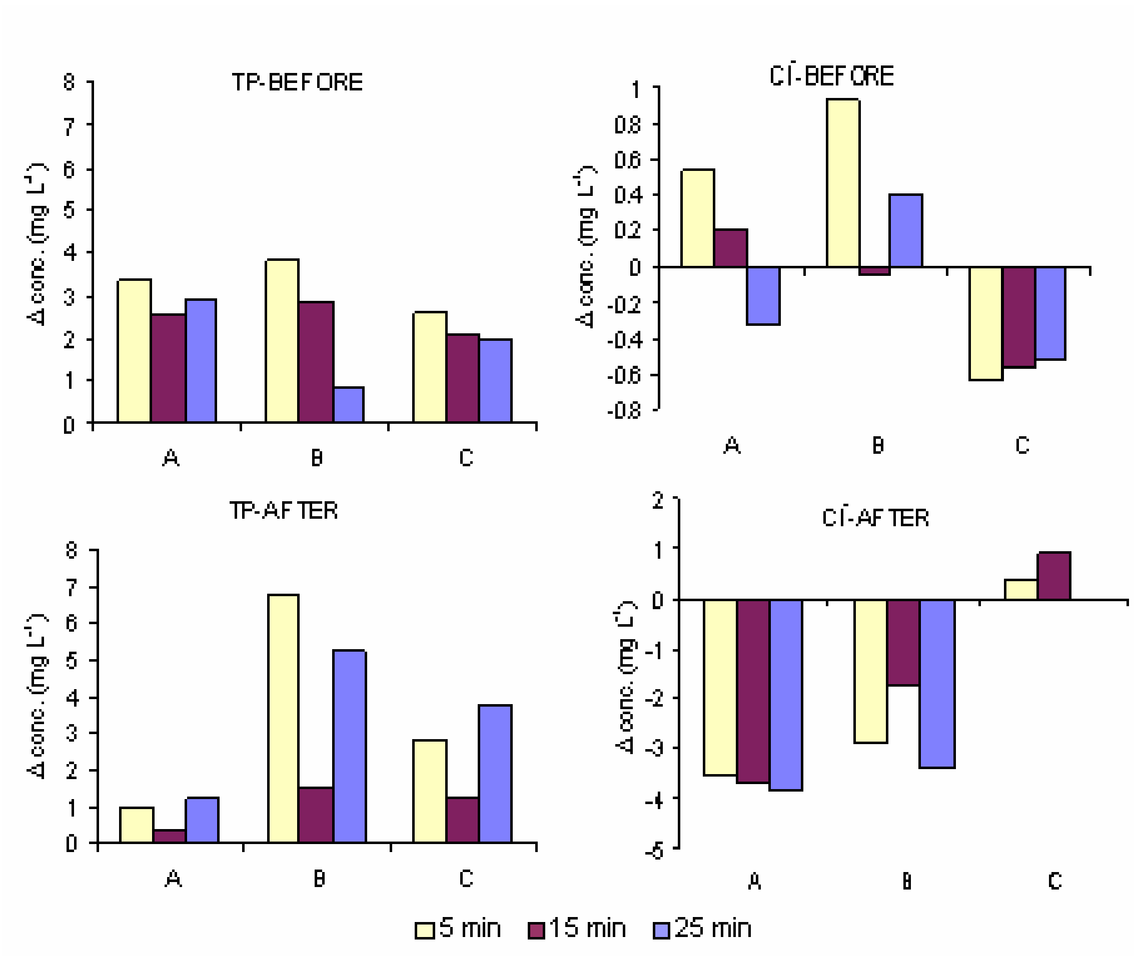
- Sampling time: the time after runoff initiation.
- 'BEFORE' refers to rainfall simulation tests before manure addition (1998); 'AFTER' refers to those after manure addition (2000).
- SD: standard deviation
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.

Chemistry

The changes in concentrations and loading rates with time for TP and Cl$^-$ in BEFORE and AFTER are shown in Fig. 4.4 and 4.5 (Appendix G1).

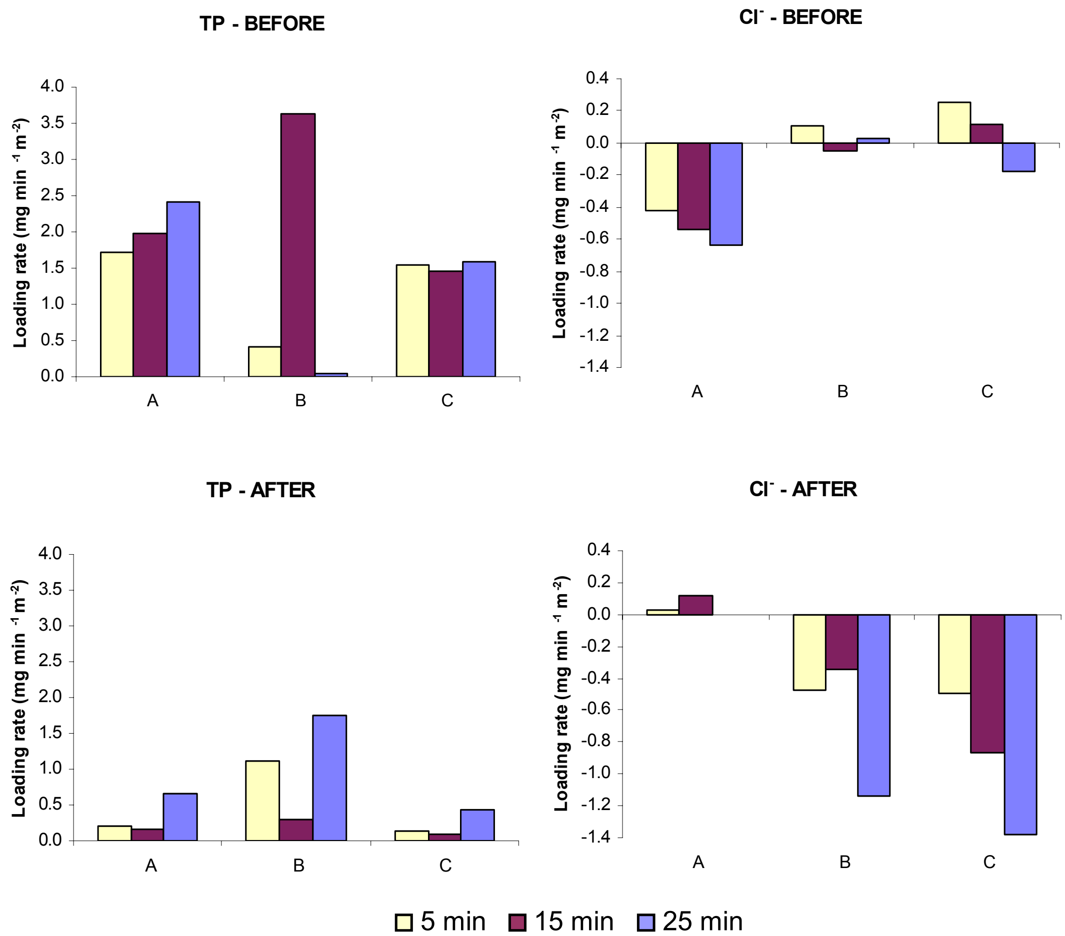
In Fig. 4.4, TP data for BEFORE always had the highest TP value at 5 min, and TP for AFTER always had the lowest value at 15 minutes. However, Cl$^-$ data exhibited no generally similar patterns between watersheds. For individual watersheds, the control (A) watershed had a similar pattern between BEFORE and AFTER in both TP and Cl$^-$ but consistencies of patterns between BEFORE and AFTER were not found in the manured (B and C) watersheds (Fig. 4.4). However, the temporal changes of chemistry in watershed A might be too small to account for trends.

When the data are presented as loading rates in Fig. 4.5, the patterns are quite different from the concentration data, reflecting the general increase in runoff rate with time (Table 4.8).



Note:
- Each value is a single measurement at 5, 15, and 25 minutes after runoff initiation in a specific simulation on back slope position of specific watershed.
- 'BEFORE' refers to rainfall simulation test conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000).
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.
- Δ conc. = Δ concentration = runoff chemical concentration – simulated rain chemical concentration

Fig. 4.4: Temporal Runoff chemistry (Δ conc.) – Perdue.



Note:

- Each value is a single measurement at 5, 15, and 25 minutes after runoff initiation in a specific simulation on the back slope position of the given watershed.
- 'BEFORE' refers to rainfall simulation test conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000).
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.

Fig. 4.5: Temporal Runoff chemical loading rate (mg min^{-1} m^{-2})
– Average of three slope positions – Perdue

4.2.5 Soil Nutrient Supply Rates

The results of Plant Root Simulator Probes for measuring soil NO_3-N, NH_4-N and PO_4-P supply rates are summarized in Table 4.12, with more parameters listed in Appendix I1.

Table 4.12: Soil (0 – 5 cm depth) nutrient supply rates (μg 10 cm^{-2} 24 h^{-1}) as assessed by plant root simulator probes – Perdue.

Watershed	Slope position	BEFORE			AFTER		
		NO_3-N	NH_4-N	P	NO_3-N	NH_4-N	P
		μg 10 cm^{-2} 24 h^{-1}			μg 10 cm^{-2} 24 h^{-1}		
A	shoulder	<2	4	0.7	22	2	0.6
	back	8	8	1.6	11	1	1.2
	foot	21	4	2.5	10	3	3.0
B	shoulder	4	4	20.8	100	9	2.6
	back	33	3	3.7	156	2	2.7
	foot	41	5	6.7	124	6	1.9
C	shoulder	<2	3	10.5	192	5	1.0
	back	<2	3	2.9	27	9	4.4
	foot	6	2	0.9	167	8	5.2
Method Detection Limits:		2	2	0.2	2	2	0.2

Note:

- 'BEFORE' refers to rainfall simulation tests conducted before manure addition (1998); 'AFTER' refers to those after manure addition (2000).
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.

In the control watershed (A), no significant differences (t-test, α=0.10) were found between BEFORE and AFTER for soil NO_3-N, NH_4-N and resin-extractable P. For manured watersheds, significant differences (t-test, α=0.10) are found in soil NO_3-N of watershed B, with AFTER having greater values. However, despite each NO_3-N reading in AFTER being greater than BEFORE, the differences between BEFORE and AFTER in Watershed C were not tested statistically significant (t-test, α=0.10), probably due to the great variation within the measurements. When watersheds B and C are combined, significant differences between BEFORE and AFTER appear in soil NO_3-N and NH_4-N supply rates, with AFTER being greater (Table 4.12).

Fisher's protected LSD (α=0.10) was used to test the significance of differences in soil nutrient supply rates between watersheds, and the results are summarized in

Table 4.13. For BEFORE, no significant differences between watersheds were found in soil NO_3-N, NH_4-N, and P supply rates. For AFTER, significant differences between watersheds were found in soil NH_4-N (C≥B≥A, C>A) and NO_3-N (C=B>A) supply rates. There were no significant differences in soil P supply rates between watersheds in AFTER (Table 4.13).

Table 4.13: Fisher's protected LSD test results (α=0.10) of soil nutrient supply rates (as assessed by plant root simulator probes) between watersheds – Perdue.

Watershed	BEFORE			AFTER		
	P	NH_4-N	NO_3-N	P	NH_4-N	NO_3-N
A	a	a	a	a	b	b
B	a	a	a	a	ab	a
C	a	a	a	a	a	a

Note:
- 'BEFORE' refers to data before manure addition (1998); 'AFTER' refers to that of after manure addition (2000).
- Different symbols indicate significant difference (α=0.10) amongst watersheds (i.e. "a" is for the higher value; "b" is for the lower value). The same symbol indicates no significant differences between watersheds.
- There were three measurements for each watershed.
- Watershed A, B, and C each received liquid hog manure at a rate of 0, 79, and 112 m^3 ha^{-1}, respectively, by low disturbance injection method, using disk openers followed by knife injectors in fall 1999.

A Spearman rank correlation was performed to test for relationships between soil nutrient supply rates and runoff chemistry (Table 4.14). With the combined data of BEFORE and AFTER, soil N has significant correlations with runoff N, but a significant relationship was not found between soil P and runoff P.

Table 4.14: Spearman rank correlation significance of runoff chemistry as compared to soil nutrient supply rates – Perdue

Soil	Runoff	Perdue		
		Both	BEFORE	AFTER
TN	NH_4-N	***		
TN	NO_3-N	**	*	
NH_4-N	NH_4-N	**		
NH_4-N	NO_3-N	***		**
NO_3-N	NO_3-N	**	*	
P	TP			
P	OP		***(▼)	

Note:
- 'BEFORE' refers to data before manure addition (1998); 'AFTER' refers to that of after manure addition (2000); 'Both' refers to data of grouping BEFORE and AFTER.
- Sample size: 9 for BEFORE, 9 for AFTER, and 18 for Both.
- Significant correlations at different significance level: '*' for α=0.10, '**' for α=0.05, '***' for α=0.01.
- '(▼)' refers to negative relationship

4.3 Rainfall Simulation Tests – Elstow

In the following sections covering the Elstow site, 'BEFORE' refers to rainfall simulation tests conducted before manure addition (fall 2000 for watersheds A, C, D, E and fall 2001 for watershed B), and 'AFTER' (spring 2002) refers to those conducted after manure addition. Manure was applied to the watersheds in Fall 2001. One rainfall simulation test was conducted at each slope position (shoulder, back, and foot) at all watersheds for both BEFORE and AFTER. One additional rainfall simulation test was conducted on the back slope position (back-2) at all Elstow watersheds in 2002. All back-2 additional rainfall simulation tests were conducted before seeding with the exception of the one in watershed D, which was done after seeding (Appendix G2). Table 3.7 provides a summary of events and timelines. The back-2 data were excluded in all figures and statistical analyses.

4.3.1 Water Quality of Simulated Rainfall

The water used for the simulated rainfall tests was sampled and analyzed for the same parameters as those for runoff, and results were summarized in Table 4.15 (Appendix G2). The water source used for all rainfall simulation tests in both BEFORE and AFTER was the groundwater from a local well. The water chemistry used for simulated rain between years was similar for all parameters, with exception of Cl^-, which was about 3 times lower in 2000 than in 2001 and 2002. Water source of rainfall simulation tests for the Elstow site was well water, and thus no fecal coliform was detected.

Table 4.15: Water quality of water used in rainfall simulation tests – Elstow.

Year	Watershed	TP	OP	NH_4-N	NO_3-N	DOC	Cl^-	Fecal Coliform
		mg L^{-1}						ct $100mL^{-1}$
2000	BEFORE	0.005	<0.002	0.203	0.081	4.4	6.5	<1
2000	(ACDE)	0.006	<0.002	0.186	0.089	2.3	7.0	<1
	Average	0.006	<0.002	0.195	0.085	3.4	6.8	<1
	Range	0.001	<0.002	0.017	0.008	2.1	0.5	<1
2001	B	0.004	0.003	0.171	0.114	2.9	21.9	<1
2002	AFTER	0.004	<0.002	0.198	0.086	2.5	23.0	<1
2002	(ABCDE)	0.005	<0.002	0.183	0.060	2.8	21.7	<1
	Average	0.005	<0.002	0.191	0.073	2.7	22.3	<1
	Range	0.001	<0.002	0.015	0.026	0.3	1.2	<1

Note:
- BEFORE: 2000 (watersheds ACED) and 2001 (watershed B); AFTER: 2002
- 'SD' refers to standard deviation, and 'Range' is the difference between maximum and minimum.

4.3.2 Runoff Initiation Time and Runoff Rate

Table 4.16 shows the data of runoff initiation time. The average time to generate runoff was 5.0 (SD of 4.4) minutes for BEFORE, and 14.7 (SD of 6.2) minutes for AFTER. For BEFORE, more time was generally required to generate runoff at the shoulder position than other landscape positions. There were significant differences in time needed to initiate runoff (t-test, α=0.10) between BEFORE and AFTER, with AFTER taking on average almost three times longer (Table 4.16).

For the duplicate rainfall simulation tests in the back slope positions (back-2) in AFTER, There were no significant differences (t-test, α=0.10) between back and back-2. Between back and back-2 slope positions in AFTER, the greatest difference in runoff initiation time between back and back-2 was in watershed D (19.9 minutes), where the watershed was seeded between the back and back-2 tests.

Table 4.16: Runoff initiation time (min) – Elstow.

Watershed	Slope position	BEFORE (min)	AFTER (min)
A	shoulder	9.8	10.5
	back	1.5	13.6
	foot	1.2	18.1
B	shoulder	8.8	11.1
	back	1.4	11.5
	foot	1.5	5.7
C	shoulder	15.5	9.8
	back	6.7	15.5
	foot	7.5	5.0
D	shoulder	1.0	12.2
	back	1.8	7.6
	foot	0.9	7.8
E	shoulder	8.9	17.5
	back	3.9	30.0
	foot	4.6	10.1
A	back-2		8.3
B	back-2		8.8
C	back-2		26.6
D	back-2		27.5
E	back-2		36.3

Note:

- 'BEFORE' refers to rainfall simulation tests before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- 'back-2' is the duplicate rainfall simulation test on back slope position of each watershed for AFTER.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

The runoff rates during the sampling periods were calculated using Eq. 3.4 and Eq. 3.5 or Eq. 3.6, and the results are presented in Table 4.17 (Appendix H2). On all slope positions (shoulder, back, and foot), runoff samples were taken at 15 minutes after runoff initiation. The average runoff rates during sampling at 15 minutes after runoff initiation were 1.40 (SD of 0.92) mm min^{-1} m^{-2} for BEFORE, and 1.43 (SD of 0.61) mm min^{-1} m^{-2} for AFTER. No significant differences (t-test, α=0.10) were found when comparing either BEFORE and AFTER or back and back-2. For both BEFORE and AFTER, the lowest runoff rates were measured at the foot slope positions, with the exception of watershed D in BEFORE and watershed E in AFTER.

Table 4.17: Runoff rate (mm min^{-1} m^{-2}) during sampling at 15 minutes after runoff initiation – Elstow

Watershed	Slope position	BEFORE (mm min^{-1} m^{-2})	AFTER (mm min^{-1} m^{-2})
A	shoulder	1.24	1.84
	back	1.81	2.47
	foot	1.22	1.23
B	shoulder	0.56	2.09
	back	0.44	1.70
	foot	0.37	1.23
C	shoulder	0.59	1.56
	back	1.61	1.16
	foot	0.29	1.10
D	shoulder	1.57	2.57
	back	3.60	1.08
	foot	2.06	0.78
E	shoulder	2.48	0.74
	back	2.03	0.52
	foot	1.13	1.32
A	back-2		2.53
B	back-2		2.32
C	back-2		1.46
D	back-2		0.56
E	back-2		0.82

Note:
- 'BEFORE' refers to rainfall simulation tests before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- 'back-2' is the duplicate rainfall simulation test on back slope position of each watershed for AFTER.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

Even though runoff rates were monitored throughout rainfall simulation tests, the data were only directly relevant to runoff chemistry when they corresponded to sample collection. Sampling at 5 and 25 minutes was only done on back slope positions and therefore only back slope positions were used to assess the change in runoff rate with time. For both BEFORE and AFTER, runoff rates during sampling were lowest at 5 minutes after runoff initiation in all watersheds (Table 4.18, Appendix H2).

Table 4.18: Temporal runoff rate (mm min^{-1} m^{-2}) during sampling – back slope positions of Elstow

Watershed	Sampling time (min)	BEFORE (mm min^{-1} m^{-2})	AFTER (mm min^{-1} m^{-2})	AFTER – back-2 (mm min^{-1} m^{-2})
A	5	0.86	1.76	0.72
	15	1.81	2.47	0.82
	25	3.04	2.97	0.01
B	5	0.43	0.64	1.26
	15	0.44	1.70	2.53
	25	1.17	2.26	3.09
C	5	0.78	0.94	2.03
	15	1.61	1.16	2.32
	25	3.54	1.23	2.71
D	5	2.07	0.44	0.83
	15	3.60	1.08	1.46
	25	4.58	1.75	2.04
E	5	0.52	0.42	0.26
	15	2.03	0.52	0.56
	25	3.79	0.64	0.82

Note:
- Sampling time: the time after runoff initiation.
- ‘BEFORE’ refers to rainfall simulation tests before manure addition (2000 for ACDE, 2001 for B); ‘AFTER’ refers to those after manure addition (2002); ‘AFTER – back-2’ refers to the duplicate rainfall simulation tests on back slope positions in AFTER.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

4.3.3 Runoff Water Quality

The runoff samples collected from rainfall simulation tests were submitted for coliform tests and chemical analyses. In this section, results from runoff samples collected at 15 minutes after runoff initiation were used to represent the runoff water quality of each simulation.

Coliforms

Runoff samples were collected only at back slope positions for BEFORE, and at all slope positions (shoulder, back, and foot) for AFTER. All runoff samples were submitted for the fecal coliform tests, with the exception of shoulder, back, and foot slope positions of watershed D for AFTER, which were mislabeled and were submitted for total coliform tests. Runoff samples collected at back-2 slope position of watershed D for AFTER were submitted for both total and fecal coliform tests.

In AFTER, fecal coliform concentrations of the shoulder and back slope positions in watershed D could be assumed as <1 (ct $100mL^{-1}$), since their total coliform concentration were <1 ct $100mL^{-1}$ (Table 4.19). With this assumption, only one (foot slope position of watershed D in AFTER) from all runoff samples collected at 15 minutes after runoff initiation had a possibility of having fecal coliform concentration >1 (ct $100mL^{-1}$).

The generally low concentrations of fecal coliforms in the water used for rainfall simulation tests (Table 4.15) and in runoff (Table 4.19) indicated that there was no fecal contamination of the runoff water passing over the soil where manure had been applied.

Table 4.19: Coliform concentrations (ct 100 mL^{-1}) of runoff samples (collected at 15 minutes after runoff initiation) from rainfall simulation tests – Elstow.

Watershed	Slope position	BEFORE	AFTER	
		Fecal Coliform (ct 100mL^{-1})	Fecal Coliform (ct 100mL^{-1})	Total coliform (ct 100mL^{-1})
A	shoulder		<1	
A	back	<1	<1	
A	foot		<1	
B	shoulder		<1	
B	back	<1	<1	
B	foot		<1	
C	shoulder		<1	
C	back	<1	<1	
C	foot		<1	
D	shoulder			<1
D	back	<1		<1
D	foot			429
E	shoulder		<1	
E	back	<1	<1	
E	foot		<1	
A	back-2		<1	
B	back-2		<1	
C	back-2		<1	
D	back-2		<1	131
E	back-2		<1	

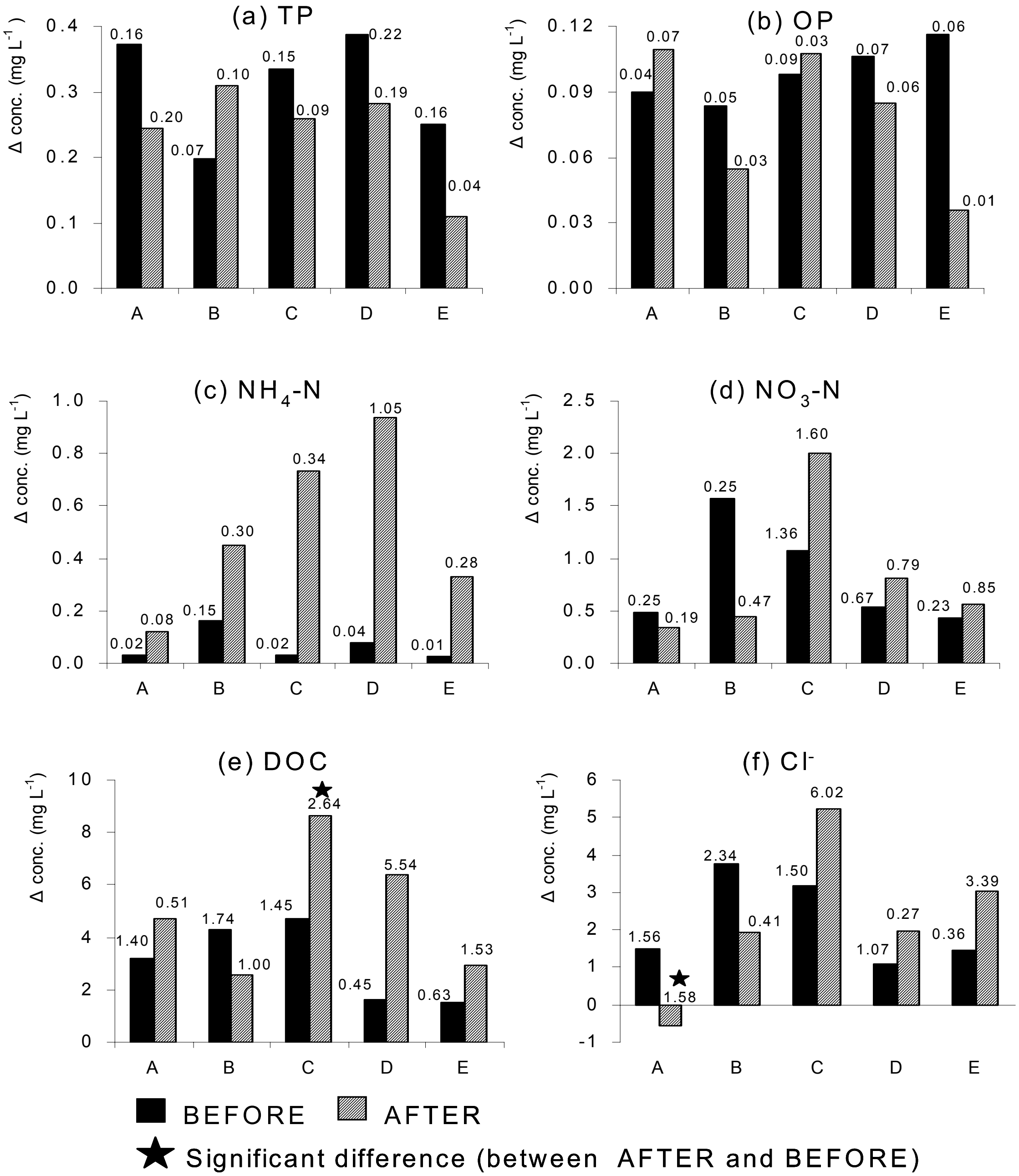
Note:

- ‘BEFORE’ refers to rainfall simulation tests before manure addition (2000, 2001); ‘AFTER’ refers to those conducted after manure addition (2002).
- ‘back-2’ is the duplicate rainfall simulation test on back slope position of each watershed for AFTER.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

Chemistry

When comparing runoff chemistry data between BEFORE and AFTER, background chemistry of the simulated rain (Table 4.15) was subtracted. Delta concentration (Δ conc. = original runoff chemistry – simulated rain chemistry) is used to present the independent differences in chemical concentrations between runoff and the simulated rainfall, and the original runoff chemical concentrations can be found in Appendix G2. Figure 4.6 shows the effects of the various manure treatments on the runoff chemistry to be independent of rain source. Each value in Figure 4.6 is the average of the three measurements of the slope positions (shoulder, back, and foot) in specified watershed.

In the control watershed (A), the only significant difference (t-test, α=0.10) in chemical concentration between BEFORE and AFTER was found in Cl^-, with AFTER being 2 mg L^{-1} lower on average. In the manured watersheds (B, C, D, and E), there were no significant differences between BEFORE and AFTER in all chemical parameters, with the exception of DOC in watershed C. Although there was no statistically significant difference, manured watersheds tended to have increases in NH_4-N and NO_3-N in AFTER, especially for watersheds C, D, and E (Fig. 4.6).



Note:

- Each value is the average of the three measurements of the slope positions (shoulder, back, and foot) in specified watershed.
- Δ conc. = Δ concentration = average runoff chemistry – average rain chemistry.
- Numbers above bars are standard deviations.
- 'BEFORE' refers to data before manure addition (ACDE for 2000, B for 2001); 'AFTER' refers to those obtained after manure addition (2002 for all watersheds). Significance of difference is determined by a paired two-tailed t-test at α=0.10.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

Fig. 4.6: Runoff chemistry (Δ conc.) – Average of three slope positions – Elstow

When all the manured watersheds (BCDE) were grouped to test for differences between BEFORE and AFTER (t-test, α=0.10), no significant differences were found in all chemical parameters except for NH_4-N. Ammonium-N in AFTER was more than eight times higher on average than in BEFORE (Appendix G2).

The significance of differences in runoff chemistry between different manure treatments was determined using Fisher's protected LSD test (α=0.10), and the results are summarized in Table 4.20. In BEFORE, the only significant difference between treatments was found in DOC (B=C≥A≥D=E, B=C>D=E). In AFTER, no significant differences between treatments were found in any parameters, regardless of the fact that each watershed received a different manure treatment.

Table 4.20: Fisher's protected LSD test results (α=0.10) of runoff chemistry (Δ conc.) between watersheds – Elstow.

	Watershed	TP	OP	NH_4-N	NO_3-N	DOC	Cl^-
BEFORE	A	a	a	a	a	ab	a
	B	a	a	a	a	a	a
	C	a	a	a	a	a	a
	D	a	a	a	a	b	a
	E	a	a	a	a	b	a
AFTER	A	a	a	a	a	a	a
	B	a	a	a	a	a	a
	C	a	a	a	a	a	a
	D	a	a	a	a	a	a
	E	a	a	a	a	a	a

Note:

- 'BEFORE' refers to rainfall simulation tests before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- Different symbols indicate significant difference (α=0.10) amongst watersheds (i.e. "a" is for the higher value; "b" is for the lower value). The same symbol indicates no significant differences between watersheds.
- There were three measurements for each watershed.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

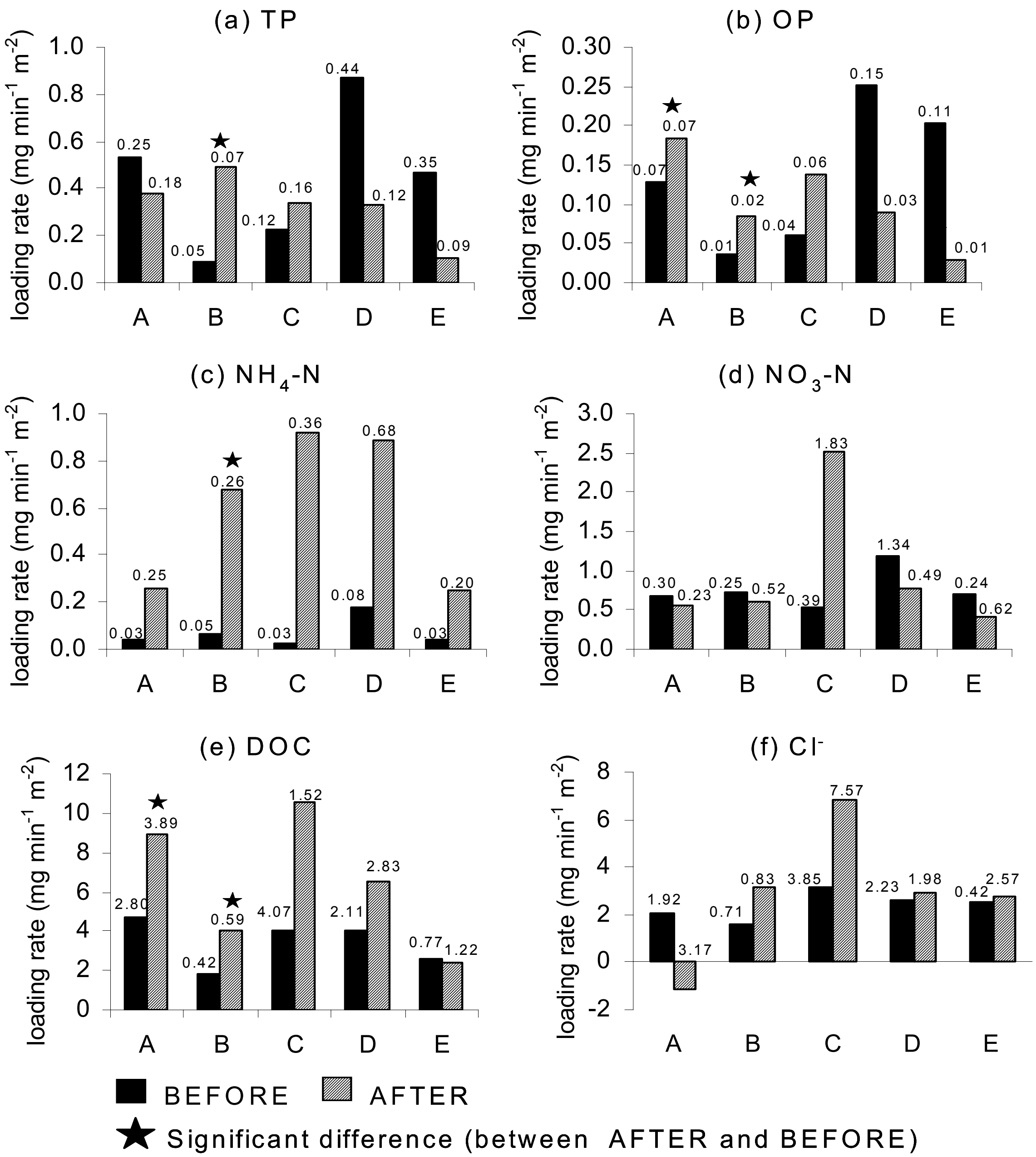
To examine the differences between the two manure application rates, data from those watersheds with the same manure application rate were combined in a paired two-tailed t-test (Appendix G2). In both BEFORE and AFTER, there were no significant differences between the high manure application rate (CE) and the low manure application rate (DB) for all chemical parameters.

To examine the differences between the two different manure injection methods, data from those watersheds with the same injection method were combined in a paired two-tailed t-test (Appendix G2). In BEFORE, there were no significant differences between the regular disturbance injection method (CD) and the low disturbance injection method (EB). In AFTER, significant differences appeared in OP and DOC, with the regular disturbance injection method (CD) having higher average concentrations than the low disturbance injection method (EB).

The average chemical loading rates of all rainfall simulation tests within the same watershed were plotted in Fig. 4.7. Each value in Figure 4.7 is the average of the three measurements of the slope positions (shoulder, back, and foot) in a specified watershed. A paired two-tailed t-test was used to test the significance (α=0.10) of differences between BEFORE and AFTER. In the control watershed (A), only OP and DOC loading rates were significantly different between BEFORE and AFTER, with AFTER having higher averages. In the manured watersheds, watershed B had significant different loading rates of TP, OP, NH_4-N, and DOC, with AFTER having higher average loading rates. Watersheds C, D, and E had no significant differences (t-test, α=0.10) in any chemical parameter (Fig. 4.7) between BEFORE and AFTER. When all manured watersheds (BCDE) were grouped, significant differences were found for NH_4-N and DOC between BEFORE and AFTER, with AFTER having higher loading rates on average.

When comparing Fig. 4.6 to 4.7, similar patterns between watersheds were found in all chemical parameters for AFTER but not for BEFORE, indicating that runoff rate (Table 4.17) may have had a stronger influence than chemical concentration in the calculation of loading rate for BEFORE.

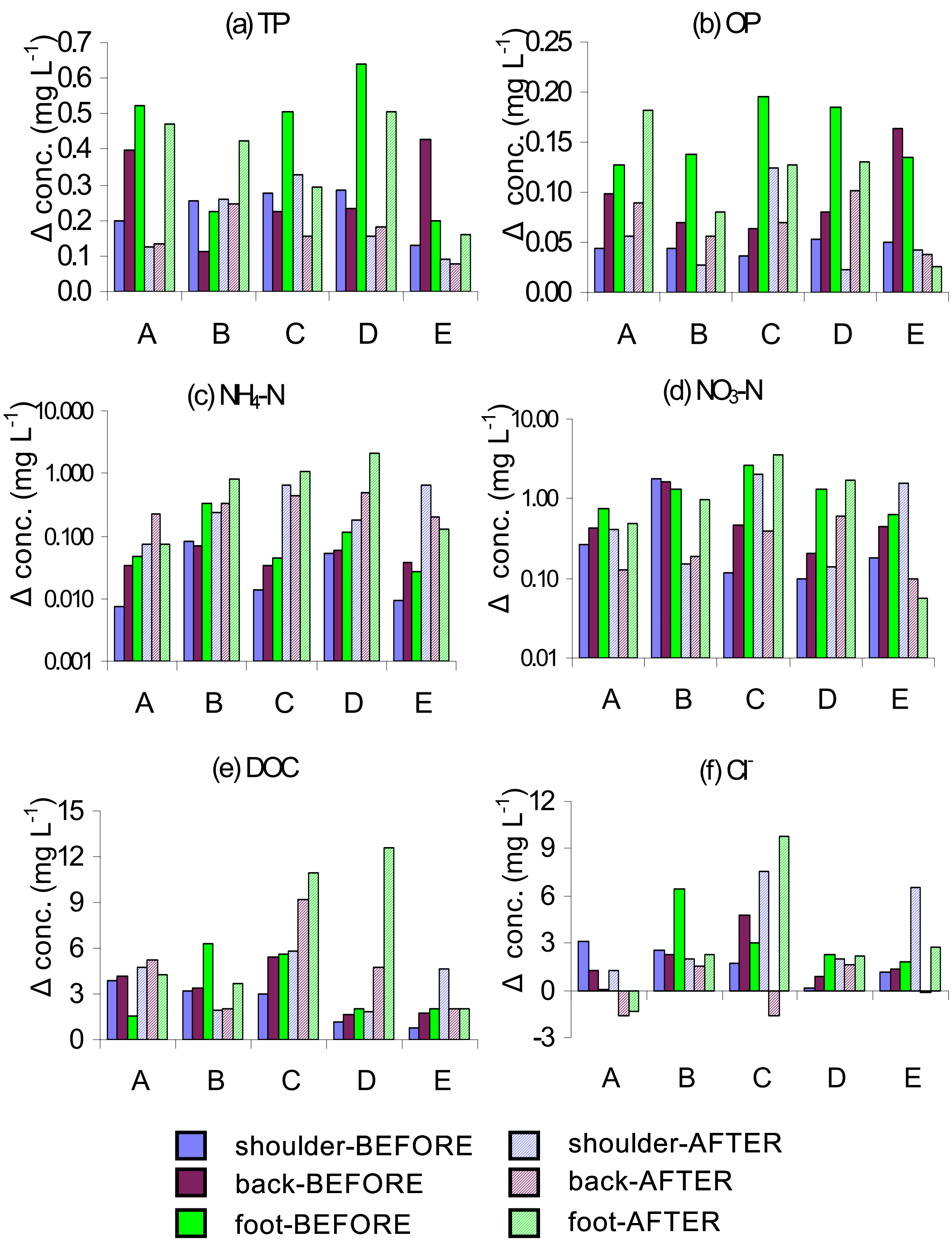
The runoff chemistry from rainfall simulation tests conducted on all slope positions (shoulder, back, and foot) at all five watersheds is plotted in Fig. 4.8 (Appendix G2). In BEFORE, a visual trend, shoulder < back <foot slope positions, was found in OP and, to some degree, in NH_4-N. After manure addition, no consistent trends were found with regards to slope positions (Fig. 4.8).



Note:

- Each value is the average of the three measurements of the slope positions (shoulder, back, and foot) in specified watershed.
- Numbers above bars are standard deviations.
- 'BEFORE' refers to data before manure addition (ACDE for 2000, B for 2001); 'AFTER' refers to those obtained after manure addition (2002 for all watersheds). Significance of difference is determined by a paired two-tailed t-test at α=0.10.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

Fig. 4.7: Runoff chemical loading rate (mg min^{-1} m^{-2}) – Average of three slope positions – Elstow.



Note:

- Δ conc. = Δ concentration = runoff chemical concentration – simulated rain chemical concentration.
- 'BEFORE' refers to data before manure addition (ACDE for 2000, B for 2001); 'AFTER' refers to those obtained after manure addition (2002 for all watersheds). Significance of difference is determined by a paired two-tailed t-test at α=0.10.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

Fig. 4.8: Runoff chemistry (Δ conc.) – Three slope positions – Elstow.

Fisher's protected LSD was used to determine the significance of differences (α=0.10) in runoff chemistry between slope positions in the manured watersheds (BCDE), and the results were summarized in Table 4.21. In BEFORE, the only significant differences between slope positions appeared in OP (foot > back > shoulder slope positions). In AFTER, the only significant difference between slope positions was seen in the TP data (foot ≥ shoulder ≥ back, foot > back). The lack of consistency in TP and OP between BEFORE and AFTER indicates that the effect of slope positions changed after manure addition, or the differences between slope position were not that strong to show on Fisher's protected LSD tests.

Table 4.21: Fisher's protected LSD test (α=0.10) results of runoff chemistry between slope positions – Elstow.

	Slope position	TP	OP	NH_4-N	NO_3-N	DOC	Cl^-
BEFORE	shoulder	a	c	a	a	a	a
	back	a	b	a	a	a	a
	foot	a	a	a	a	a	a
AFTER	shoulder	ab	a	a	a	a	a
	back	b	a	a	a	a	a
	foot	a	a	a	a	a	a

Note:

- 'BEFORE' refers to data before manure addition (ACDE for 2000, B for 2001); 'AFTER' refers to those obtained after manure addition (2002 for all watersheds).
- Different symbols indicate significant difference (α=0.10) amongst watersheds (i.e. "a" is for the higher value; "b" is for the lower value). The same symbol indicates no significant differences between watersheds.
- There were four measurements (watersheds BCDE) for each slope positions.

4.3.4 Temporal Runoff Water Quality

The runoff samples collected at 5, 15, and 25 minutes after runoff initiation were used to analyze the relation of the chemical and coliform concentrations to time. Only rainfall simulation tests at the back slope positions had complete collections at these times for TP, Cl^-, and coliforms (Appendix G2).

Coliforms

All runoff samples collected at back slope positions in the Elstow site were submitted for the fecal coliform tests, with the exception of watershed D for AFTER, and the results are shown in Table 4.22. Runoff samples collected at the back slope position of watershed D for AFTER were mislabeled and were submitted for only total coliform tests. Runoff samples collected at back-2 slope position (the duplicate rainfall simulation test) of watershed D for AFTER were submitted for both total and fecal coliform tests.

The fecal coliform concentrations of the 15-minute data at the back slope position in watershed D for AFTER could be assumed as <1 ct $100mL^{-1}$, since its total coliform concentration was <1 ct $100mL^{-1}$ (Table 4.22). With this assumption, only two data (5-minute and 25-minute data at the back slope position of watershed D in AFTER) from all runoff samples collected at back slope positions had a possibility of having fecal coliform concentration >1 (ct $100mL^{-1}$).

There seemed no change of coliform concentrations with time, since in most cases the concentrations were all < 1 ct $100mL^-1$. The generally low concentrations of fecal coliforms in the water used for rainfall simulation tests (Table 4.15) and in runoff (Table 4.22) indicated that there was no fecal contamination of the runoff water passing over the soil where manure had been applied.

Table 4.22: Temporal coliform concentrations (ct $100mL^{-1}$) of runoff from rainfall simulation test – back slope positions at Elstow.

Watershed	Sampling time (min)	BEFORE	AFTER		AFTER – back -2	
		Fecal Coliform (ct $100mL^{-1}$)	Fecal Coliform (ct $100mL^{-1}$)	Total coliform (ct $100mL^{-1}$)	Fecal Coliform (ct $100mL^{-1}$)	Total coliform (ct $100mL^{-1}$)
A	5	<1	<1		<1	
	15	<1	<1		<1	
	25	<1	<1		<1	
B	5	<1	<1		<1	
	15	<1	<1		<1	
	25	<1	<1		<1	
C	5	<1	<1		<1	
	15	<1	<1		<1	
	25	<1	<1		<1	
D	5	<1		254	<1	34400
	15	<1		<1	<1	131
	25	1		<10	<1	48800
E	5	1	<1		<1	
	15	<1	<1		<1	
	25	<1	<1		<1	

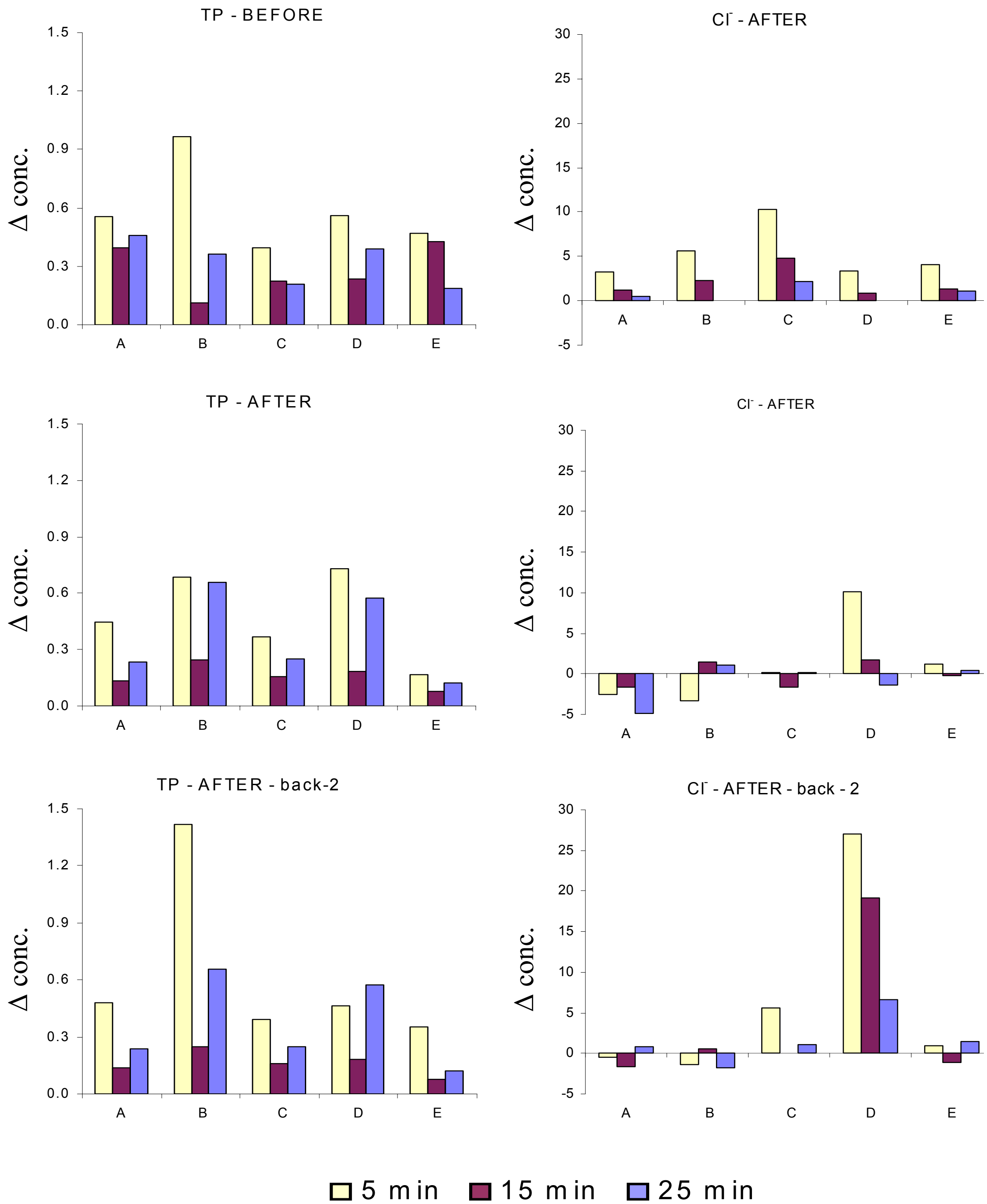
Note:
- Sampling time: the time after runoff initiation.
- 'BEFORE' refers to rainfall simulation test before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- 'back-2' is the duplicate rainfall simulation test on back slope position of each watershed for AFTER.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 $m^3\ ha^{-1}$, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

Chemistry

The changes in delta concentrations (Δ conc.) and loading rates with time for TP and Cl^- in BEFORE and AFTER are shown in Fig. 4.9 and 4.10, respectively. In AFTER, back-2 is the duplicated rainfall simulation tests on the back slope positions.

In Fig. 4.9, TP of BEFORE had the highest values at 5 minutes after runoff initiation, and the lowest value at 15 minutes with the exception of watershed E. For TP of AFTER and AFTER back-2, the highest concentrations appeared at 5 minutes and the lowest values were at 15 minutes, with the exception of watershed D in 'back-2', which was the only back-2 rainfall simulation test conducted after seeding (Fig. 4.9). For Cl^- concentrations of BEFORE, the highest concentration occurred at 5 minutes, and then gradually decreased with time. For Cl^- of AFTER and AFTER back-2, no consistent patterns of trends were found (Fig. 4.9).

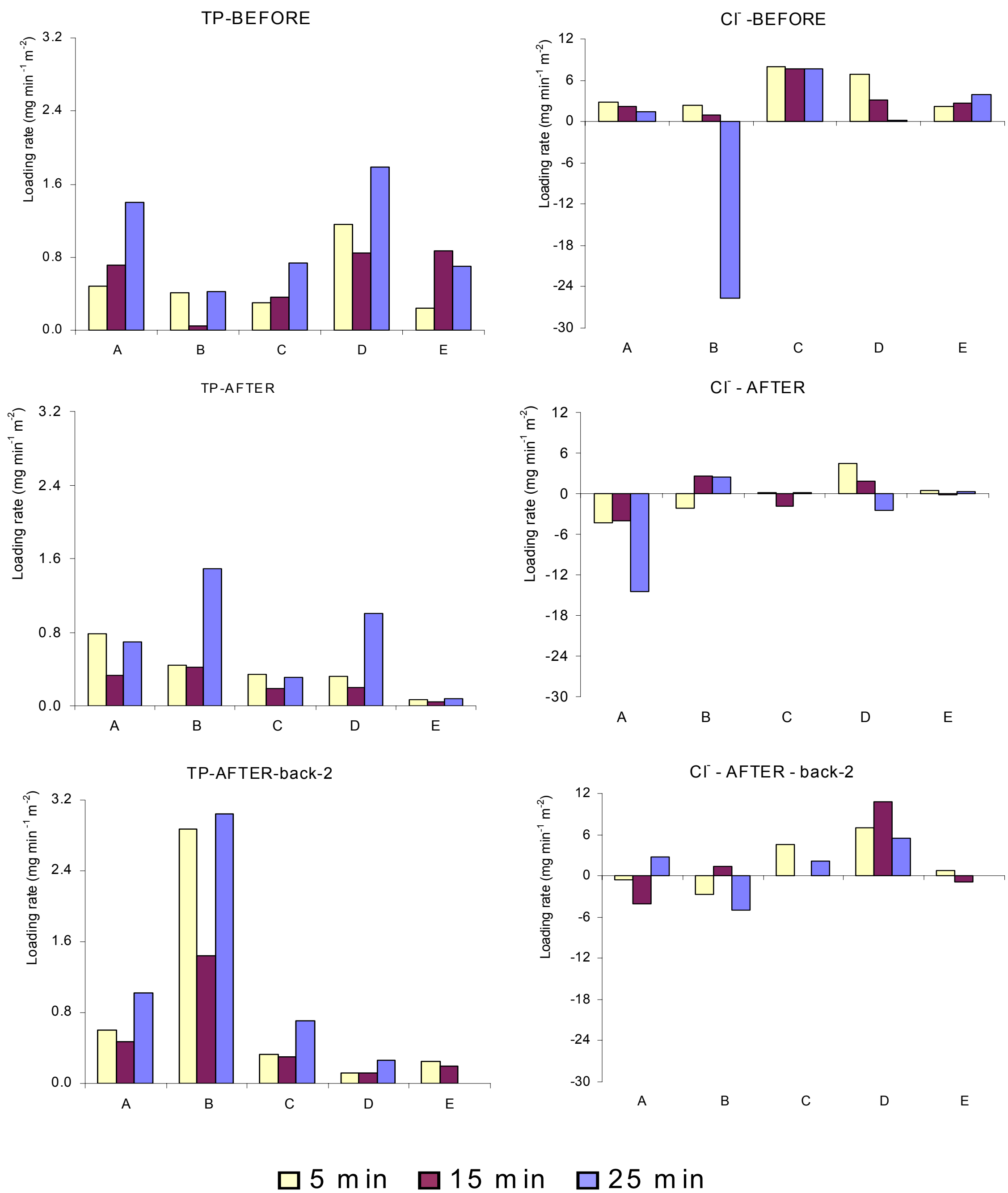
When comparing patterns in delta concentration (Fig. 4.10) and chemical loading rate (Fig. 4.10), no visually consistent patterns of trends were found for both TP and Cl^-, with the exception of AFTER-back for Cl^-. The absence of consistent patterns indicates that differences in runoff rate with time may have masked the weight of chemical concentrations in the calculations (Eq. 3.7).



Note:

- 'BEFORE' refers to rainfall simulation test before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.
- Δ conc. = Δ concentration = average runoff chemistry – average rain chemistry.

Fig. 4.9: Temporal Runoff chemistry (Δ conc.) – Elstow.



Note:

- 'BEFORE' refers to rainfall simulation test before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

Fig. 4.10: Temporal runoff chemical loading rate (mg min^{-1} m^{-2}) – Elstow

4.3.5 Soil Nutrient Supply Rates

In the control watershed (A), no significant differences (t-test, α=0.10) were found between BEFORE and AFTER for soil NO_3-N, NH_4-N and P supply rates (Table 4.23). In the watersheds receiving manure (watersheds B, C, D and E), only watershed D had a significant difference in soil NO_3-N supply rates, with AFTER having a greater average value than BEFORE. The lack of significant differences could due to some extreme values in the limited sample numbers and thus high variability.

Table 4.23: Soil (0 – 5 cm depth) nutrient supply rates (μg 10 cm^{-2} 24 h^{-1}) as assessed by plant root simulator probes – Elstow.

Watershed	Slope position	BEFORE			AFTER		
		P	NH_4-N	NO_3-N	P	NH_4-N	NO_3-N
		μg 10 cm^{-2} 24 h^{-1}			μg 10 cm^{-2} 24 h^{-1}		
A	shoulder	1.4	5	< 2	1.4	5	6
	back	1.5	5	10	4.2	2	3
	foot	2.1	6	178	3.8	3	140
B	shoulder	0.5	5	< 2	1.4	19	159
	back	2.2	8	< 2	0.9	8	151
	foot	1.0	25	< 2	1.8	45	25
C	shoulder	1.0	4	72	0.8	31	117
	back	2.2	6	104	0.7	4	89
	foot	1.6	7	29	0.9	11	138
D	shoulder	0.7	5	55	1.0	59	124
	back	1.2	4	47	1.9	16	106
	foot	2.9	15	< 2	1.1	104	60
E	shoulder	1.2	4	89	1.4	14	91
	back	1.2	5	28	1.2	9	28
	foot	1.0	7	< 2	2.0	53	2
A	back-2				0.9	2	<2
B	back-2				0.8	5	166
C	back-2				8.1	164	<2
D	back-2				1.4	35	59
E	back-2				1.0	10	174
Method Detection Limits:		0.2	2	2	0.2	2	2

Note:
- 'BEFORE' refers to rainfall simulation test before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.
- 'back-2' is the duplicate rainfall simulation test on back slope position of each watershed for AFTER.

When all manured watersheds (BCDE) were combined, significant differences between BEFORE and AFTER appeared in soil NO_3-N and soil NH_4-N, with AFTER being greater.

Fisher's protected LSD was used to determine the significance (α=0.10) of differences in soil nutrient supply rates between watersheds, and the results are summarized in Table 4.24. For BEFORE, no significant differences (α=0.10) were found between all watersheds in soil P, NH_4-N, and NO_3-N supply rates. For AFTER, soil P of the control watershed A was significantly higher (α=0.10) than all other watersheds that received manure (watersheds B, C, D, and E). No significant differences were found between watersheds in soil NO_3-N and NH_4-N, even though watersheds B, C, D, and E each received different manure treatment and were higher in nutrient supply than the control (Table 3.5).

Table 4.24: Fisher's protected LSD test results (α=0.10) of soil nutrient supply rates (as assessed by plant root simulator probes) between watersheds – Elstow.

Watershed	BEFORE			AFTER		
	P	NH_4-N	NO_3-N	P	NH_4-N	NO_3-N
A	a	a	a	a	a	a
B	a	a	a	b	a	a
C	a	a	a	b	a	a
D	a	a	a	b	a	a
E	a	a	a	b	a	a

Note:

- 'BEFORE' refers to rainfall simulation test before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- Different symbols indicate significant difference (α=0.10) amongst watersheds (i.e. "a" is for the higher value; "b" is for the lower value). The same symbol indicates no significant differences between watersheds.
- There were three measurements for each watershed.
- Watersheds A, B, C, D, and E each received liquid hog manure at a rate of 0, 56, 90, 56, and 90 m^3 ha^{-1}, respectively, in fall 2001. Manure was applied to Watersheds C and D by regular disturbance manure injection method using shovel openers, and to watersheds B and E by low disturbance injection method using disc opener.

Fisher's protected LSD (α=0.10) was also performed on soil nutrient supply rates to determine the significant differences between slope positions of the manured watersheds (BCDE), and the results were summarized in Table 4.25. For BEFORE, no significant differences (α=0.10) in soil P and NO_3-N were found between slope positions; however, foot slope position had greater NH_4-N than should and back slope positions. For AFTER, no significant differences (α=0.10) in soil P and NO_3-N were found between slope positions; however, foot slope position had greater NH_4-N than back slope position. Overall, foot slope position had highest NH_4-N than upper slope positions (shoulder and back).

Table 4.25: Fisher's protected LSD test results (α=0.10) of soil nutrient supply rates (as assessed by plant root simulator probes) between slope positions – Elstow.

	Slope position	P	NH_4-N	NO_3-N
BEFORE	shoulder	a	b	a
	back	a	b	a
	foot	a	a	a
AFTER	shoulder	a	ab	a
	back	a	b	a
	foot	a	a	a

Note:
- 'BEFORE' refers to rainfall simulation test before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- Different symbols indicate significant difference (α=0.10) amongst watersheds (i.e. "a" is for the higher value; "b" is for the lower value). The same symbol indicates no significant differences between watersheds.
- There were four measurements (watersheds BCDE) for each slope positions.

A Spearman rank correlation was performed to test for relationships between soil nutrient supply rates and runoff chemistry (Table 4.26). When data from BEFORE and AFTER were combined, a strong correlation was found between Soil NH_4-N and Runoff NH_4-N, and a weak correlation between Soil P and Runoff OP was noted.

Table 4.26: Spearman rank correlation significance of runoff chemistry as compared to soil nutrient supply rates – Elstow

Soil	Runoff	Elstow		
		Both	BEFORE	AFTER
TN	NH_4-N			
TN	NO_3-N			
NH_4-N	NH_4-N	***		
NH_4-N	NO_3-N		***	*(▼)
NO_3-N	NO_3-N			
P	TP			
P	OP	*		

Note:
- 'BEFORE' refers to rainfall simulation test before manure addition (2000, 2001); 'AFTER' refers to those conducted after manure addition (2002).
- Sample size: 15 for BEFORE, 15 for AFTER, and 30 for Both.
- Significant correlations at different significance level: '*' for α=0.10, '**' for α=0.05, '***' for α=0.01.
- '(▼)' refers to negative relationship

5. DISCUSSION

Due to the similarities between runoff chemistry (Δ conc.) and loading rate data, only runoff chemistry (Δ conc.) will be considered when discussing the changes in runoff chemistry.

Due to the shallow soil-water interaction zone (0-3 mm depth of soil), soil nutrient supply rates of surface soil (0 – 5 cm depth) were discussed along with runoff nutrient concentrations to illustrate the changes of runoff chemistry as affected by manure addition.

5.1 General Discussion

This section addresses the general issues regarding data quality control, problems with instrumentation, interpretation of general physical properties, temporal variability of runoff chemistry during rainfall simulation test, and correlation between runoff and soil nutrient supply rates.

5.1.1 Elstow and Perdue

Weather during rainfall simulation test periods was drier and warmer than the long-term climatic averages. No major rainfall events occurred in the two weeks prior to or during any of the rainfall simulation test periods (Appendix A1). Therefore, the differences in soil moisture prior to rainfall simulation tests within years were considered negligible.

The water chemistry of the simulated rain changed between years and sources (Table 4.5 and Table 4.15). To eliminate the influence of rainfall chemistry on runoff chemistry, runoff chemistry was presented as 'delta concentration (Δ conc.)' (i.e. Δ concentration = original runoff chemistry – simulated rain chemistry) to show the independent differences between BEFORE and AFTER. The negative values might be due to the analytical and instrumental errors (for Cl^-) or the great variation in the chemistry of the water used for rainfall simulation test (for all other parameters).

The same equipment was used throughout each series (e.g. all rainfall simulation tests for BEFORE were defined as one series) of rainfall simulation tests; therefore, the possible effects of simulator/rainfall intensity on runoff chemistry should be similar between watersheds and slope positions in the same series of rainfall simulation tests (BEFORE or AFTER).

Ground cover might play an important role in influencing the mechanism of runoff and infiltration; however, the information was not collected for all rainfall simulation tests. Due to lack of information of ground cover, it was assumed that ground cover in BEFORE and AFTER was similar, and therefore did not affect the runoff chemistry.

Temporal data (Fig. 4.4 and 4.9) of Cl^- concentrations in runoff (collected at 5, 15 and 25 minutes after runoff initiation) showed no consistent trends with time. The general trend of TP temporal data after manure addition (high at 5 minutes, low at 15 minutes, and high again at 25 minutes) indicated the possible change in the relative proportions of OP and particulate-associated P that accounted for TP. However, temporal data of OP and sediment loading were not collected to determine the change of OP and particulate-P with time. According to the increasing runoff rate with time (Table 4.8 and 4.18), higher soil erosion and particulate-P could be expected with time. Thus, it suggested that OP might be the major contributor to the high TP at 5-minute sampling, and particulate-P might be the major contributor to the high TP at 25-minute sampling.

When the data from Perdue and Elstow were combined in regression tests between soil nutrient supply rates and runoff chemistry (Table 4.14, Table 4.26), a strong correlation (α=0.05) between soil N supply rates and runoff N, especially NH_4-N, was found. Since surface runoff interacts mostly with surface soil, the strong correlation between soil NH_4-N supply rate and runoff NH_4-N concentration suggests that soil NH_4-N supply rate may be a good index to predict runoff NH_4-N concentration. However the generally weak correlation between soil P and runoff P suggests that soil P is not a good indicator for runoff P.

5.1.2 Perdue

Different water sources were used in BEFORE and AFTER (a new dugout for BEFORE, and well water for AFTER). In BEFORE, the water chemistry of the five samples of simulated rain was similar; whereas in AFTER great ranges of chemistry were found in NO_3-N (0.695 and 2.310 mg L^{-1}) and Cl^- (29.1 and 33.3 mg L^{-1}) between the two samples of simulated rain (Table 4.5). This could be due to the disturbance of the sediment in well water during pumping. However, the influence of this great variation on runoff chemistry was eliminated by using the two chemical results of simulated rain separately when calculating runoff chemical Δ concentration (i.e. Δ concentration = runoff chemistry – simulated rain chemistry) for AFTER rainfall simulation tests.

A different rainfall simulator was used for the AFTER (2000) tests than that of BEFORE (1998), resulting in 124% higher average rainfall intensity (Table 3.8) than BEFORE with a significant difference (t-test, α=0.10). Despite the higher rainfall intensities of the AFTER tests, the average runoff rate of AFTER (during sampling at 15 min after runoff initiation) was 71% lower than BEFORE (Table 4.7) and the difference was significant (t-test, α=0.10). It was observed that the rain generated by the AFTER simulator had a 'misty' appearance and thus of smaller drop size which could have affected soil surface crusting and thus infiltration rate. Moreover, although not statistically significant (t-test, α=0.10), the runoff initiation time of AFTER was generally higher than that of BEFORE (Table 4.6). Lower runoff rates (with significant differences by t-test, α=0.10) and generally higher runoff initiation times in AFTER both indicated that AFTER had higher infiltration or lower rain energy than BEFORE, which likely resulted in lower soil erosion and less particulate-associated transport. This might explain the generally lower runoff chemical Δ concentrations in AFTER for the control watershed (Fig. 4.1).

5.1.3 Elstow

Even though the same simulator and equipment was used in Elstow for both BEFORE and AFTER, rainfall intensity had a large standard deviation within each series (e.g. all rainfall simulation tests for BEFORE were defined as one series) (Table 3.8). This could be due to the low uniformity (43%) of rainfall pattern and the slight variation of placement location of rain gauges. However, similar variation existed in all rainfall simulation tests by the same equipment. Since the same ground equipment and simulator was used for all rainfall simulation tests at the Elstow site, the effects of low uniformity on runoff quality between rainfall simulation tests can be ignored.

The average rainfall intensity (Table 3.8) of AFTER (2002) was significantly different than BEFORE (2001 and 2000), (t-test, α=0.10), with AFTER being lower. With the same equipment, the difference of intensity between BEFORE and AFTER was not expected to be significant. The significant difference in recorded intensity might be due to the low rainfall uniformity and variation in rain gauge location. Although the difference in rainfall intensity between BEFORE and AFTER was statistically significant, the hydrological consequences appeared to be minimal.

The mean runoff initiation time of AFTER was statistically different (t-test, α=0.10) than BEFORE, with AFTER taking longer than BEFORE (Table 4.16). To check if the longer runoff initiation time was caused generally by weather or by manure application, the data were divided into control and manured watersheds when comparing BEFORE and AFTER. The paired two-tailed t-test (α=0.10) results showed that control did not have significant difference in runoff initiation time; whereas manured watersheds needed almost 130% more time (with a significant difference, α=0.10) to initiate runoff in AFTER then in BEFORE. This indicated that after manure application, the soils in the manured watersheds might infiltrate more water before generating runoff, which agreed with data by Assefa (2002) that showed higher infiltration after manure application.

Despite the lower rainfall intensity of AFTER than BEFORE (Table 3.8) with significant differences (t-test, α=0.10), the runoff rates during sampling at 15 min after runoff initiation were not significantly different (t-test, α=0.10) between BEFORE and AFTER (Table 4.17). Since rainfall intensity did not appear to have affected runoff rate, there likely should not be any effect on runoff chemistry caused by runoff rate.

5.2 General Effects of Liquid Hog Manure Application upon Runoff Water Quality

To study the general effects of manure application on runoff chemistry, data from all watersheds that received manure are combined in all statistical analyses and presented as “manured watersheds”. Before discussing the effects of manure addition, possible factors other than manure that may have caused the differences between the control and manured watersheds were investigated to clarify their effects on changes in soil nutrient supply rates and runoff chemistry. Then the differences of soil nutrient supply rates and runoff chemistry between BEFORE and AFTER were examined both for the control and for manured watersheds to reveal the effects of manure application.

The changes in runoff chemistry between BEFORE and AFTER in the control watershed (A) could be considered as a outcome of all the possible effects from experimental operation (e.g. rainfall simulators change, highly variable chemistry of water used in rainfall simulation test, change of protocol and operators) and natural changes of inherent properties (e.g. weather, soil nutrient supply rates of surface soil, soil structure, watershed differences), excluding the effects of manure application.

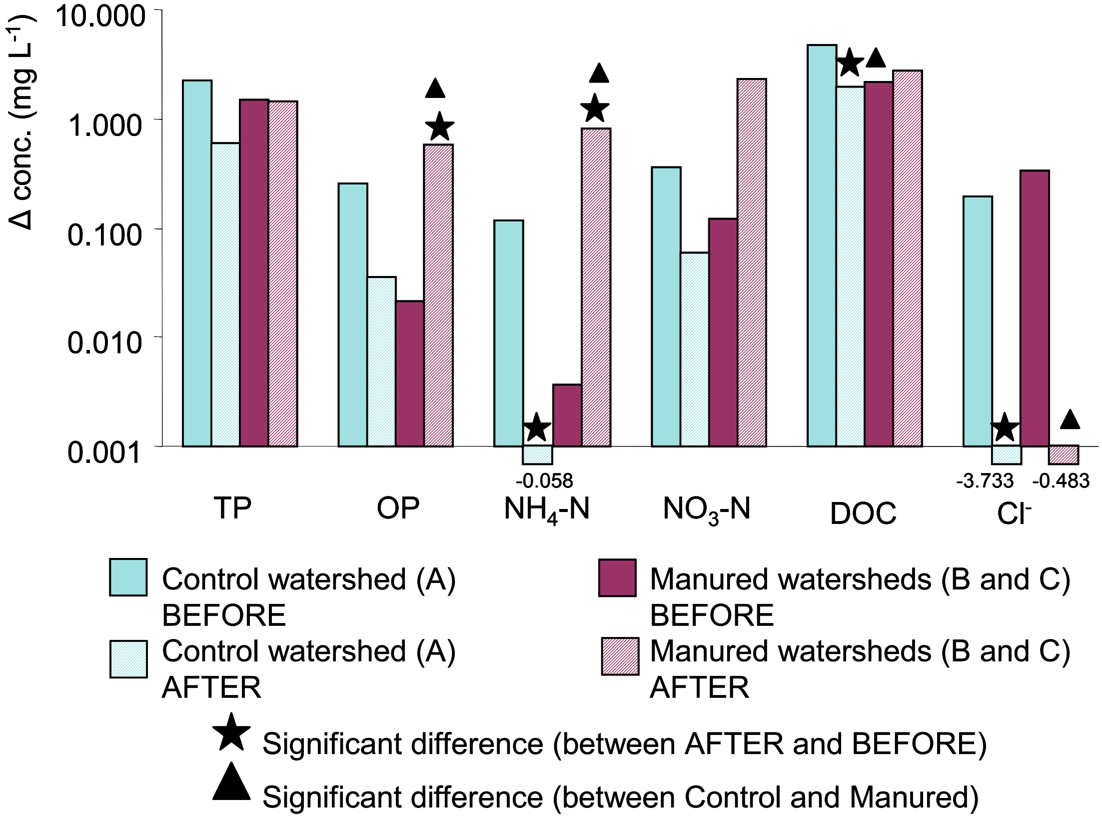
5.2.1 Perdue

Different crops were grown in the control (barley) and manured (CPS wheat) watersheds at Perdue (Table 3.3) in 1998 prior to the BEFORE rainfall simulation tests in the fall of 1998. According to the publication by Canadian Fertilizer Institute (2001) on nutrient uptake and removal by field crops, barley is expected to uptake more N (112 – 137 kg ha^{-1}) and P (20 – 24 kg ha^{-1}) than spring wheat (85 – 104 kg N ha^{-1}, 14 – 17 kg P ha^{-1}). Therefore, in BEFORE, there may have been less available soil N and P left on the control watershed than on the manured watersheds. However, the slight differences of soil P, NH_4-N, and NO_3-N nutrient supply rates between control and manured watersheds in BEFORE were not statistically significant (t-test, α=0.10) (Table 4.12). Thus, the effects of different crop type on the differences of soil N and P between control and manured watersheds were considered negligible in the Perdue BEFORE rainfall simulation tests.

The soil nutrient supply rates of AFTER had significant differences (t-test, α=0.10) between control and manured watersheds in soil NH_4-N and NO_3-N nutrient supply rates, with manured watersheds having higher means. However, soil P nutrient supply rate did not change significantly. The same crop was planted in all watersheds in the year (1999) prior to when data of AFTER (spring 2000) were collected (Table 3.3). Crop uptake was therefore likely similar on both the control and manured watersheds prior to the AFTER rainfall simulation tests. With similar effects of inherent changes between watersheds, the addition of manure to the manured watersheds was the most likely cause of the higher soil NH_4-N and NO_3-N nutrient supply rates in the manured watersheds than the control watershed.

Figure 5.1 displays the comparisons of runoff chemistry between control and manured watersheds, along with the changes between BEFORE and AFTER. Runoff chemistry of BEFORE shows no significant differences (t-test, α=0.10) between the control and manured watersheds in all chemical concentrations except DOC, where the manured watersheds had the lower mean. After manure addition (AFTER), significant differences between the control and manured watersheds (t-test, α=0.10) appeared in OP and NH_4-N concentrations (with manured watersheds having higher values), and in Cl^- concentration (with manured watersheds having lower the mean). The inconsistency of trends in control and manured between BEFORE and AFTER indicated that initial differences between control and manured watersheds in BEFORE were masked by other stronger influences. With the same equipment used throughout each rainfall simulation test year, the higher chemical concentrations in the manured watersheds than the control watershed were likely caused by manure addition. The higher mean runoff NH_4-N concentration in the manured watersheds than the control watershed reflected the mean soil NH_4-N supply rate that was also higher on the manured watersheds with a significant difference (t-test, α=0.10) in AFTER (Fig. 5.1, Table 4.12).

The changes of soil and runoff chemistry in the control watershed between BEFORE and AFTER were indicative of the overall differences in runoff chemistry that



Note:

- The significances of differences were determined by two-tailed t-tests (α=0.10).
- There were 3 measurements for the control watershed, and 6 measurements for the manured watersheds (both in BEFORE and AFTER).

Fig. 5.1: Runoff chemistry (Δ conc.) – control and manured watersheds – Perdue.

were due to a range of influences that occurred in all watersheds. These influences include changes in equipment, operators, and protocols, and plant uptake by different crops, natural degradation / loss / deposition of soil nutrients, climate but exclude the effects of manure addition.

When comparing AFTER to BEFORE in the control watershed (A), soil nutrient supply rates (Table 4.12) showed no significant differences (t-test, α=0.10) in soil P, NH_4-N, and NO_3-N supply rates. Runoff chemistry of AFTER in the control watershed had generally lower concentrations of all parameters than BEFORE (Fig. 5.1) with significant differences (t-test, α=0.10) occurring for NH_4-N, DOC, and Cl^-.

When comparing AFTER to BEFORE in the manured watersheds, soil P supply rates (Table 4.12) were not significant different (t-test, α=0.10). However, soil NH_4-N and NO_3-N supply rates had higher averages in AFTER (Table 4.12) with significant differences (t-test, α=0.10), even with a single manure application. Runoff chemistry of the manured watersheds showed evidence of increased OP and NH_4-N concentrations with significant differences (t-test, α=0.10) after manure addition (Fig. 5.1). Unlike the general decreases in all parameters of runoff and soil nutrient supply rates in the control watershed, the manured watersheds had general increases in runoff chemical concentrations (with exceptions of TP and Cl^-) and soil NH_4-N and NO_3-N supply rates. These increases in the manured watersheds were most likely due to manure addition (Table 4.12, Fig. 5.1).

Overall, runoff OP and NH_4-N had higher concentrations (significantly different by t-test, α=0.10) both when comparing manured watersheds to the control, and AFTER to BEFORE (Fig. 5.1). This is a clear indication of the general effects of manure addition on runoff chemistry.

5.2.2 Elstow

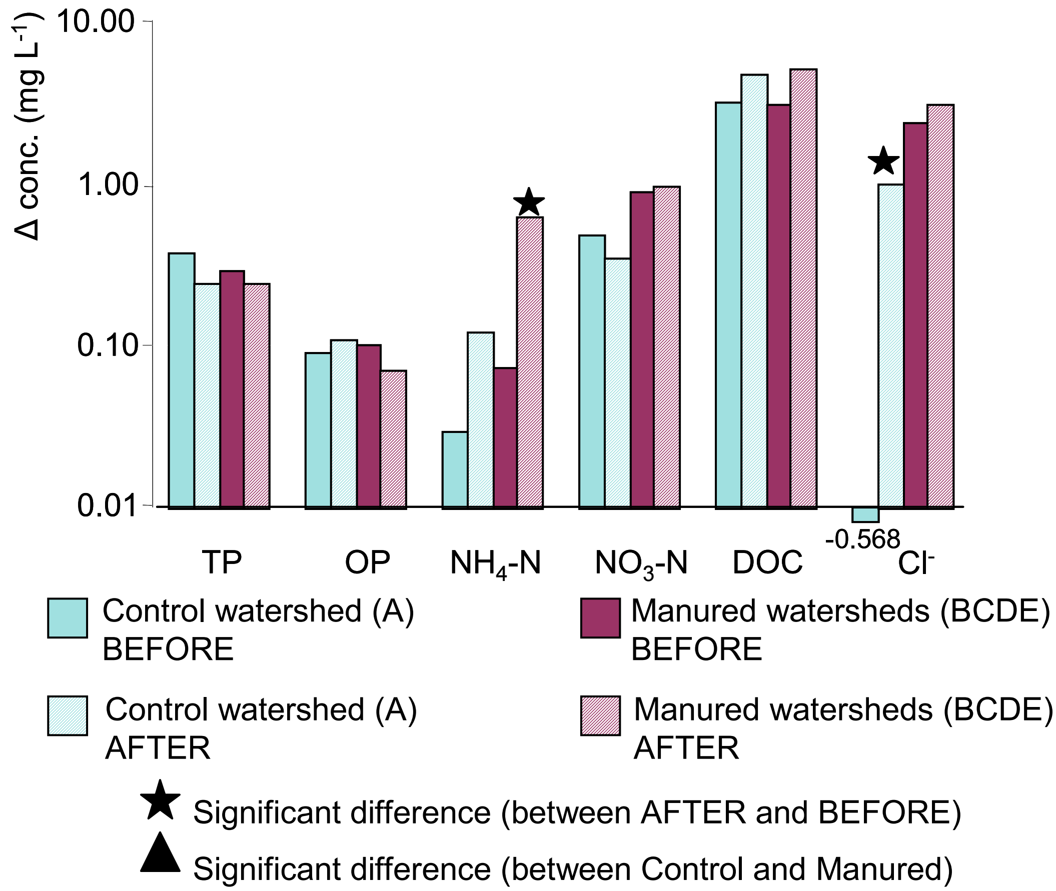
Different crops were grown in the control (peas) and manured (canola) watersheds (2001, Table 3.6) prior to data collection for AFTER (Spring 2002); thus, the effects of different crop type on soil nutrient supply rates should be considered.

Despite the higher uptake of N and lower uptake of P expected for peas (155 – 188 kg N ha^{-1}, 19 – 23 kg P ha^{-1}) than canola (112 – 138 kg N ha^{-1}, 23 – 28 kg P ha^{-1}) (Canadian Fertilizer Institute, 2001), peas normally contributes to soil N via N fixation from the atmosphere. A review by Evans et al. (2001) gave the range of the net effect of peas on soil N balance (i.e. the difference between fixed N and N harvested in legume grain) as –46 (depletion) to 181 (addition) kg N ha^{-1}, and used crop-specific models to estimate the average addition of 40 kg N ha^{-1} by peas in Australia. In Saskatchewan, additional N benefit from peas was estimated to be 15 – 40 kg N ha^{-1} (Beckie et al., 1997). Therefore, as compared to manured watersheds, the control watershed could be expected to leave only slightly more N and P in the soil than the manured watersheds by the end of 2001 growing season, prior to data collection for AFTER (spring 2002). Additionally, unlike the manured watersheds, prior to rainfall simulation test of AFTER (spring 2002) the control watershed had no chemical fertilizer applied in spring 2001 (Table 3.5).

Before manure addition (BEFORE), no significant differences (t-test, α=0.10) in soil P, NH_4-N, and NO_3-N supply rates were found between the control and manured watersheds. After manure application (AFTER), there were no significant differences (t-test, α=0.10) in soil P and NO_3-N supply rates between the control and manured watersheds. However, in AFTER, the average of soil NH_4-N supply rate of the control became lower than the manured watersheds with a significant difference (t-test, α=0.10) despite the soil N addition by peas and lack of chemical fertilizer application in the control watershed. This appeared to be an indication of an increase in soil NH_4-N supply rate caused by manure addition, which also appeared in the Perdue data.

Figure 5.2 displays runoff chemistry comparing the control and manured watersheds, along with changes between BEFORE and AFTER. Runoff chemistry of BEFORE showed no significant differences (t-test, α=0.10) between control and manured watersheds in all parameters. After manure additions (AFTER), the only significant differences (t-test, α=0.10) appeared in runoff NH_4-N concentration with manured watersheds having a higher mean concentration than the control watershed. The increased runoff NH_4-N concentration was consistent with higher soil NH_4-N supply rates in the manured watersheds.

On the control watershed (A), when comparing AFTER to BEFORE (Table 4.23) there were no significant differences in soil P, NH_4-N, and NO_3-N supply rates. Runoff chemistry of the control watershed (Fig 5.2) showed no significant differences (t-test, α=0.10) in any parameters except Cl^-, where AFTER had a higher average. Even though more soil P could be left in the soil prior to data collection for AFTER due lower plant uptake, soil P and runoff TP and OP of the control watershed showed no significant differences (t-test, α=0.10) between BEFORE and AFTER indicating that inherent changes or operational errors did not likely impact runoff or soil nutrient supply rates between BEFORE and AFTER (Table 4.23, Fig 5.2).



Note:

- The significances of differences were determined by two-tailed t-tests (α=0.10).
- There were 3 measurements for the control watershed, and 12 measurements for the manured watersheds (both in BEFORE and AFTER).

Fig. 5.2 Runoff chemistry (Δ conc.) – control and manured watersheds – Elstow

Conversely on the manured watersheds (BCDE), when comparing AFTER to BEFORE, there were significant differences (t-test, α=0.10) in runoff NH_4-N concentration, and in soil NH_4-N and NO_3-N supply rates, with higher average values found for AFTER. Unlike the control watershed, the manured watersheds had a general increase in runoff and soil N in AFTER. Potentially lower N uptake by canola (on the manured watersheds) than peas (on the control watershed) could hold a minor influence on the N increase in soil and runoff in the manured watersheds; however, manure addition was the most likely reason (Table 4.23, Fig 5.2).

Even though soil and runoff P did not show significant changes at Elstow site, it reflected only one set of data collection after a single hog manure application and repeated applications may be necessary to cause an effect with these rates at this site. Daverede et al. (2004) applied liquid swine manure at low (33 –39 kg P ha^{-1} yr^{-1}) and high rates (66 –79 kg P ha^{-1} yr^{-1}) by different application methods (injection and surface application) for two years, and monitored P changes in runoff from simulated rainfall at different timing (one and six months after manure application). They found no significant differences of dissolved reactive P, algal-available P, and total P in runoff between control (receiving triple superphosphate, 54 kg P ha^{-1} yr^{-1}) and plots receiving manure by injection method, regardless of manure application rate and rainfall timing.

With repeated over application of P, surface soil P saturation level might increase and P could eventually be lost to surface runoff. Royer et al. (2003) monitored the long-term (8 years) influence of overapplication of liquid swine manure on the P status of a silt loam cropped to corn, as compared to a control which received chemical fertilizer at a recommended rate of 180 kg N ha^{-1} yr^{-1} and 7 –34 kg P ha^{-1} yr^{-1} for corn growing in Quebec. Swine manure was applied at the rate of 360 kg N ha^{-1} yr^{-1} on top of chemical fertilizer, resulting in 540 kg N ha^{-1} yr^{-1} and 106 – 150 kg P ha^{-1} yr^{-1} at different timing (spring, fall, or spring + fall). They found that the application of liquid hog manure at such high rates greatly increased soil TP, the degree of soil P saturation, and the labile P forms in surface soil (0 – 20 cm depth) relative to the control. The nutrient addition rates from manure application (270 – 439 kg N ha^{-1}, 24 – 51 kg P ha^{-1}) used in our research were not as high as that used by Royer et al. (2003) and may not have been sufficiently high to cause nutrients to accumulate with a single application.

5.3 Effects of Liquid Hog Manure Application Rate and Injection Method upon Runoff Water Quality

The differences in runoff chemistry and soil nutrient supply rates between manured watersheds as affected by application rate and injection method, are the major focus for the interpretation of the effects of different manure treatments on runoff chemistry. Before discussing the effects of manure application, the initial differences between watersheds prior to manure application (BEFORE) are examined (LSD, α=0.10) to clarify their effects on soil nutrients and runoff chemistry in AFTER. Soil nutrients and runoff chemistry changes between BEFORE and AFTER in the control watershed are then discussed, and used to describe natural changes of inherent properties and help with the interpretation of any changes in the manured watersheds (t-test, α=0.10). Statistical results and visual observations are both used to help interpret possible effects of manure treatments on runoff chemistry.

5.3.1 Perdue

As described in section 5.2.1, the manure application at the Perdue site was responsible for the increases in soil (NH_4-N, and NO_3-N) and runoff nutrients (OP and NH_4-N) on the manured watersheds after manure addition (t-test, α=0.10), while the control watershed had general decreases in all chemical parameters of runoff and soil nutrient supply rates (Fig 5.1). In this subsection, manured watersheds will be discussed separately according to the manure application rate they received. Liquid hog manure was applied at the Perdue site at two rates (79 m^3 ha^{-1} on watershed B, and 112 m^3 ha^{-1} on watershed C) in fall of 1999 with the same injection method, low disturbance using a knife injector (Table 3.2). Thus, based on Perdue data, only the effects of manure application rate can be discussed.

For the soil nutrient supply rates in manured watersheds (Table 4.13), both in BEFORE and in AFTER, there were no significant differences (LSD, α=0.10) between watersheds B and C in soil P, NH_4-N and NO_3-N supply rates regardless of different manure application rates. This indicated that there might be no effects of application rate for the single manure addition at the rates used in Perdue.

The lack of significant differences in the statistical analysis could be due to the insufficient difference between the rates used, or the limited sample size. In order to show the effect of manure application rate on soil nutrient supply rates, studies in the literature usually used larger differences (double or triple rates) in application rates. The combination of limited sample numbers and high variability of soil nutrient supply rates (Table 4.12) is also of concern. Even though each soil sample was bulked from several samples collected from the same rainfall simulation test locations, only three measurements (one at shoulder, back, and foot slope positions) were collected from each watershed.

In BEFORE, no significant differences (LSD, α=0.10) in runoff chemistry were found between watersheds B and C (Table 4.10). However, after manure addition, watershed B displayed significantly (LSD, α=0.10) greater concentrations of runoff TP, OP, and NH_4-N than watershed C despite the lower manure application rate used in watershed B (Table 4.10). For runoff NO_3-N and DOC concentration, even though no significant differences were found between watersheds B and C, average values of watershed B were again greater than C (Fig. 4.1).

The trend of runoff chemistry of AFTER with respect to manure application rate did not reflect the trend in soil nutrient supply rates of AFTER, where no significant differences were found between B and C. The only runoff chemistry parameter showing the anticipated trend with respect to manure application rate (C>B>A) with statistical significance was Cl^-. Original data collected from the field and subsequent calculations were reviewed to ensure that no errors had occurred in data processing.

A possible reason for the reversed trend in runoff TP, OP, and NH_4-N (B>C) relative to hog manure application rate (C>B) is that the steeper slopes at the rainfall simulation locations in watershed C (4 – 6 % higher than watershed B, Table 4.1) might have reduced the interaction time between soil and runoff and hence reduced runoff nutrient level. However, the runoff initiation time (Table 4.6) and runoff rate (during sampling at 15 minutes after runoff initiation, Table 4.7) of AFTER were not significantly different (t-test, α=0.10) between watersheds B and C. Therefore, the effects of slope level was not considered to be responsible for the reversed trend.

The transport of P and N from soil to runoff could be limited by the generally higher clay content in watershed C (6-11% higher than watershed B, Table 4.1). The higher clay content might have bound more nutrients and prevented them from releasing into runoff. Other possible explanations include the limited runoff sampling area from rainfall simulation tests and potential overlapping of manure application passes in the area of the sampling transect on watershed B.

5.3.2 Elstow

Two rates and two injection methods were used in the manure application at the Elstow. Watersheds C and D received manure at rates of 90 and 56 m^3 ha^{-1} by regular disturbance injection method, using shovel openers; watersheds E and B received manure at rates of 90 and 56 m^3 ha^{-1} by low disturbance injection method, using disc openers.

All watersheds receiving manure (B, C, D, and E) had the same crop type throughout the whole research period; therefore the possible effects of different crop uptake on soil or runoff chemistry differences between watersheds B, C, D, and E can be ignored.

In the manured watersheds, there were no significant differences (LSD, α=0.10) in soil nutrient supply rates between B, C, D, and E both in BEFORE and in AFTER regardless of different manure treatments (Table 4.24). Runoff chemistry of BEFORE showed the only significant difference (LSD, α=0.10) between watersheds (Table 4.20), in runoff DOC concentration (C=B≥A>D=E and B=C>D=E). In AFTER, no significant differences (LSD, α=0.10) were found between watersheds in any parameters of runoff chemical concentrations. The consistent data patterns between BEFORE and AFTER in TP, OP, NH_4-N, NO_3-N, and Cl^- indicated that no significant differences in runoff chemistry between watersheds existed at Elstow, regardless of different manure treatments. The disappearance of significant differences of DOC in AFTER showed that the differences between watersheds were masked after manure addition. The data pattern of runoff chemistry also reflected the pattern of soil nutrient supply rates.

The lack of significant differences (LSD, α=0.10) of soil and runoff nutrients between manured watersheds might indicate that a single application of the different manure treatments used in this study was not enough to produce detectable statistically significant differences. Another possible explanation for the lack of statistical significance in the LSD results might be the limited data set (three measurements for each watershed). In order to better reveal the effects of manure application rate and injection method on soil and runoff chemistry, data were combined to provide a bigger sample size for paired two-tailed t-tests (α=0.10).

To examine the significance of manure application rates, watersheds C and E were combined as the high-rate group, and watersheds D and B were combined as the low-rate group in the paired two-tailed t-test (α=0.10). Both in BEFORE and in AFTER, runoff chemistry exhibited no significant differences (t-test, α=0.10) in any runoff chemical parameters between manure application rates. Soil NH_4-N supply rates of the high-rate group in BEFORE showed a higher average than the low-rate group with significant differences (t-test, α=0.10); however, no significant differences in soil P and NO_3-N supply rates between the two groups were found. After manure addition (AFTER), no significant differences (t-test, α=0.10) in soil P, NH_4-N, and NO_3-N supply rates were found between the two groups. The disappearance of trend in soil NH_4-N supply rates between the two groups with regards to manure application rate in AFTER could be evidence that manure addition masked the initial differences of soil NH_4-N supply rates between the two groups. The absence of significant differences (t-test, α=0.10) of soil P, NH_4-N and NO_3-N supply rates for AFTER between the high-rate and the low-rate indicated that the manure nutrient addition in our research (270 – 439 kg N ha^{-1}, 24 – 51 kg P ha^{-1}) did not cause significant effects on soil nutrient supply rates of surface soil (0 – 5 cm depth) and runoff chemistry, after a single application. This might reflect some removal of nutrients from the surface layer of the soil by leaching in early spring snowmelt prior to measurement, as manure was applied in the fall of the previous year.

A similar data grouping was performed according to manure injection method, to compare the regular disturbance (watersheds C and D) with the low disturbance injection method (watersheds E and B). For soil nutrient supply rates, no significant differences (t-test, α=0.10) were found in soil P, NH_4-N, and NO_3-N supply rates between the two injection methods both in BEFORE and in AFTER. The lack of significant differences indicated that the two manure injection methods did not affect soil P, NH_4-N, and NO_3-N supply rates differently. For runoff chemistry of BEFORE, no significant differences in any runoff chemical parameters were found between the two injection methods. However, in AFTER there were significant differences (t-test, α=0.10) in runoff OP and DOC concentrations between injection methods with the regular disturbance injection method having higher average concentrations than the low disturbance injection method. This was likely due to the influences of manure injection methods, since all other possibilities were eliminated.

When comparing AFTER to BEFORE (Fig. 4.6) for the runoff chemistry of the watersheds receiving manure (B, C, D, and E), the only significant difference (t-test, α=0.10) was found for DOC concentration in watershed C, with AFTER having a higher average than BEFORE. Of the watersheds receiving manure at the high rate (C and E, 75 m^3 ha^{-1}), only watershed C, which received manure with regular disturbance injection method, had higher DOC concentration in runoff water after manure application with significant differences (t-test, α=0.10). This was the evidence for the effects of manure addition on runoff chemistry. Even one single application, with the combination of the high rate (362-51 kg N-P ha^{-1}) by the regular disturbance injection method, manure still caused increased runoff DOC, but the same rate applied with low disturbance did not negatively impact runoff chemistry, when compared to the control.

Observations of data patterns (not statistically significant by LSD at α=0.10) from Fig. 4.6 also indicated that the low soil surface disturbance injection method might be superior to regular soil surface disturbance in terms of water quality. With the regular disturbance injection method, the AFTER runoff chemistry in watershed C (high application rate) had greater values than D (low application rate) in concentrations of OP, NO_3-N, DOC, and Cl^- (Fig. 4.6). However, no visual differences of runoff chemistry were observed in watersheds B and E (treated with low disturbance injection method at two rates). In addition, watersheds C and D (regular disturbance injection method) both had higher concentrations of OP, NH_4-N, NO_3-N, and DOC than watersheds B and E (low disturbance injection method). The two rates of liquid hog manure P (33-39 and 66-79 kg P ha^{-1} yr^{-1}) applied by injection method in the research of Daverede et al. (2004) for two years were also found to have no significant effects on P (dissolved reactive P, algae available P, TP) losses in runoff from rainfall simulation tests, as compared to a control (receiving triple superphosphate, 54 kg P ha^{-1} yr^{-1}).

The data discussed above reflect a single manure addition in the cropping history. With repeated manure applications and accumulation of nutrients in soil, significant differences caused by manure application rate and/or injection methods might appear.

5.4 Effects of Landscape Position on Runoff Water Quality as Affected by Manure Application

The runoff chemistry changes as affected by slope position were evaluated in the control watershed to assist the interpretation of effects of landscape position on runoff chemistry changes in the manured watersheds. Statistical analyses and visual observations of the data patterns between slope positions are used to identify the possible effects of landscape positions in the manured watersheds.

5.4.1 Perdue

Due to the small sample size (only two measurements for each slope position), Perdue data was not suitable for statistical analysis for the comparison between BEFORE and AFTER. Therefore, visual observations of data patterns between slope positions were used to identify any possible effects of landscape positions in the manured watersheds.

Surface soil gain and loss due to soil erosion in part determines the nutrients of the surface soil, which might be lost to surface runoff. According to Pennock (2003), shoulder slope positions are expected to have the highest soil loss rate, and foot slope positions are expected to have highest soil gain in those hummocky terrain sites of southern Saskatchewan. However, at the Perdue site in this study, no consistent trends were observed in soil or runoff nutrients with respect to slope position (Table 4.12, Fig. 4.3). This could possibly be due to a single manure application in the cropping history. Differences of runoff and soil nutrient supply rates between upper and lower slope positions might be more obvious after long-term manure applications.

5.4.2 Elstow

LSD tests (α=0.10) were performed on soil and runoff nutrient of manured watersheds to determine the influence of slope positions (shoulder, back, and foot) as affected by manure application.

The soil nutrient supply rates (P, NH_4-N, and NO_3-N) only showed significant differences in NH_4-N for BEFORE (foot > back = shoulder) and AFTER (foot ≥ shoulder ≥ back, and foot > back slope positions) (Table 4.25). foot slope positions consistently had significantly greater soil NH_4-N supply rate than back slope positions, which was consistent with expected higher fertility in the foot slope position than on upper slopes (Pennock, 2003). Even though this effect might be an inherent attribute of slope positions, the average soil NH_4-N supply rate increased by 65% – 294% as an effect of manure addition (Table 4.23).

The runoff nutrient concentrations showed no significant differences between slope positions (Table 4.21), with the exception of OP of BEFORE (foot > back > shoulder slope positions) and TP of AFTER (foot ≥ shoulder ≥ back, and foot > back slope positions). The disappearance of differences between slope positions in OP after manure application might be evidence of manure addition masking the initial differences of OP between slope positions. The appearance of differences between slope positions in TP after manure application could be an effect of the manure application. Lack of significant slope position effects for other parameters differences in other parameters could be evidence of only a weak influence of slope position on soil and runoff nutrient in the very gently sloping (0 – 6.9%, Table 4.2) topography at Elstow.

5.5 Summary

5.5.1 Perdue

Despite accounting for the potential effects from differences in equipment, weather conditions, and crop type between BEFORE and AFTER at Perdue, a significant effect of manure addition rate was found to be attributed to soil and runoff chemistry change at Perdue. Even with a single manure application in the cropping history, soil NO_3-N and NH_4-N supply rates, and runoff OP and NH_4-N concentrations increased in the manured watersheds as compared to the control.

The effects of manure application rate on runoff and soil nutrient supply rates cannot be easily assessed after only a single manure application at the rates (Table 3.2) used in this research. After checking all possible reasons and mistakes, no clear explanation could be given for the seemingly greater impact of manure application at the lower rate (watershed B) than at the higher rate (watershed C) on concentrations of runoff nutrients.

5.5.2 Elstow

The effects of differences between watersheds, field fire, weather, and uneven rainfall pattern in rainfall simulation test on soil nutrient supply rates and runoff chemistry were found to be negligible for the manured watersheds. After excluding all other possibilities, manure addition most probably caused the significant increases in soil NO_3-N and NH_4-N supply rates, and in runoff NH_4-N and DOC concentrations observed in the manured watersheds.

The application rates used at Elstow (Table 3.5) had no significant effects on either soil nutrient supply rates or runoff chemistry. The effect of manure injection method showed weak impact on surface soil nutrient supply rates and inorganic nutrient ions in runoff, but did enhanced organic transport, revealed in higher concentrations of runoff OP and DOC by the regular disturbance injection method. With the combination of high rate and regular soil surface disturbance injection method, significant increases in runoff NH_4-N and DOC concentrations appeared even after one single manure application in the cropping history.

5.5.3 Perdue and Elstow

Generally, the addition of liquid hog manure caused higher N concentration, both in surface soil N supply rates (NO_3-N and NH_4-N) and runoff NH_4-N concentration with significant differences.

Increasing manure application rate within the range used in this research did not have a consistently negative impact on runoff water chemistry, with a single application. At Perdue, the highest runoff water chemistry was found in the watershed that received the lower rate of manure application. Whereas, at Elstow, the highest runoff water chemistry was measured in the watershed that received the high manure application rate with high soil surface disturbance.

Low soil surface disturbance manure injection method appeared to reduce the impact of the high application rate on runoff nutrient concentrations (especially OP, NH_4-N, and NO_3-N) at Elstow.

No substantial effects of landscape position on soil nutrient supply rates or runoff water quality were observed but replication was insufficient to fully evaluate any effects. Differences of runoff and soil nutrient supply rates between upper and lower slope positions might be more obvious after long-term repeated manure applications. Meanwhile, replication would make statistical analyses possible, and potentially lead to more conclusive comments.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The major objective of this thesis was to study the effect of manure addition, more specifically, application rate and injection method, on water chemistry of runoff from rainfall simulation tests. This objective was addressed by the analyses of runoff and soil nutrient data, and changes associated with combined treatments of manure application rate and injection method.

Generally, manure application did increase soil NH_4-N and NO_3-N supply rates in surface soil (0 – 5 cm depth), and runoff NH_4-N concentration. None of the manure treatments applied in this study caused any significant increases in fecal or total coliform in runoff from simulated rainfall events conducted 7 – 8 months after manure application. For the treatments used in this research, the type of manure injection method (regular verses low disturbance) had consistent effects on runoff chemistry but application rate did not. All the measurements of runoff chemical concentrations were below the Guidelines for Canadian Drinking Water Quality.

The manure treatments used at the Elstow site had no significant influence on runoff chemistry; however, manure application with the combination of high rate (75 m^3 ha^{-1}, 371 kg N and 44 kg P ha^{-1} yr^{-1}) and high soil surface disturbance resulted in higher runoff chemistry than treatments at lower rate (47 m^3 ha^{-1}, 232 kg N and 27 kg P ha^{-1} yr^{-1}) and with low soil surface disturbance. At the Perdue site, the low rate (79 m^3 ha^{-1}, 220-141 kg N-P ha^{-1} yr^{-1}) resulted in higher runoff chemistry than the high rate (112 m^3 ha^{-1}, 307-153 kg N-P ha^{-1} yr^{-1}).

The degree of surface soil disturbance in the manure injection methods appears to be an important factor affecting the nutrient content of runoff. Amongst the combinations of application rate and injection method used in this study (both Perdue and Elstow), the low disturbance injection method (with disc openers) used at Elstow had the least impact on runoff quality and surface soil nutrient accumulation, even with a high rainfall intensity (216 mm h^{-1}) and high nutrient application rate (306 – 439 kg N ha^{-1} and 24 – 36 P kg ha^{-1}). Therefore, from a surface water quality perspective, the low disturbance injection method used at Elstow is considered the best of the three manure injection method studied in this research.

The secondary objective was to study if runoff chemistry changed with slope positions, and is the relationship was affected by manure application. No consistent trends in runoff chemistry with respect to slope position were observed in the data collected in this study, both in the data before and after manure addition. Foot slope positions appeared to have higher surface soil NH_4-N supply rate in the surface soil (0 – 5 cm depth) than upper slope positions. However, since the trend was consistent between before and after manure addition, the distribution of NH_4-N in the landscape did not appear to be influenced by manure addition.

The regression tests between soil nutrient supply rates and runoff chemistry show that soil NH_4-N supply rates may be a good index to predict runoff NH_4-N concentration, but not P.

6.2 Recommendations

Since a single manure application has been shown to impact runoff water quality and surface soil nutrients (especially NH_4-N) in this research, long term monitoring on runoff and soil nutrient level is needed to understand transport mechanisms associated with repeated manure applications and, if necessary, to help adjust farming practice (manure application rate and injection method) in the future to avoid significant nutrient loss from soil to runoff and possible damage to the aquatic environment. The low disturbance injection method used at Elstow has the potential to decrease the impact on soil and water quality of higher manure application rates.

If long-term study is not possible, soil NH_4-N supply rate (by the plant root simulator probes) is recommended to be included in the short-term study (even with a single fertilizer application), for it appeared to be a good index of runoff NH_4-N concentration in this research.

Prior to conducting further research with rainfall simulation tests, rainfall simulator equipment should be tested to ensure reproducible rainfall intensities and even rainfall distribution. In future runoff monitoring, the inclusion of temporal data of particulate-associated P (or sediment load) in runoff chemistry and surface vegetation cover of the collecting area are suggested to give better illustration of effects of soil erosion on runoff chemistry.

To reveal the effects of slope positions on runoff chemistry, replicate rainfall simulation tests should be conducted at each slope position to minimize the effects of limited sampling area and to increase the measurement numbers for statistical analyses.

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APPENDIX A: AVERAGE MONTHLY WEATHER DATA – SASKATOON AIR PORT

A1: Average Monthly Temperature (^oC)

Month\Year	1998	1999	2000	2001	2002	1970~2002	1998~2002
1	-18.37	-17.30	-17.31	-8.93	-14.61	-14.17	-15.30
2	-5.60	-9.85	-11.17	-17.60	-8.61	-8.35	-10.57
3	-7.28	-4.48	-1.90	-3.10	-13.60	-13.19	-6.07
4	7.18	6.47	4.28	4.38	2.86	2.77	5.03
5	12.72	10.68	10.42	12.44	8.90	8.63	11.03
6	14.47	14.55	14.26	15.39	17.25	16.73	15.18
7	18.75	16.33	18.64	19.64	20.60	19.97	18.79
8	19.99	17.88	16.80	19.79	17.91	17.36	18.47
9	13.22	10.24	11.65	13.88	12.79	12.40	12.36
10	4.79	4.37	4.47	2.35	-0.87	-0.84	3.02
11	-4.22	-1.29	-6.20	-1.29	-4.51	-4.37	-3.50
12	-13.07	-7.45	-19.35	-13.38	-8.60	-8.34	-12.37

A2: Average Monthly Precipitation (mm)

Month\Year	1998	1999	2000	2001	2002	1970~2002	1998~2002
1	14.40	25.50	22.50	2.00	4.10	3.98	13.70
2	4.00	5.00	12.00	4.00	8.00	7.76	6.60
3	8.20	5.50	20.50	2.00	12.50	12.12	9.74
4	7.30	14.10	39.30	3.20	21.75	21.09	17.13
5	8.60	50.00	15.50	21.10	8.25	8.00	20.69
6	75.60	54.50	47.20	38.50	49.00	47.52	52.96
7	30.40	77.90	79.50	58.00	59.00	57.21	60.96
8	37.70	27.40	44.50	9.50	82.00	79.52	40.22
9	27.40	17.00	24.50	6.50	26.25	25.45	20.33
10	32.40	7.20	1.00	7.50	8.50	8.24	11.32
11	7.00	3.50	10.50	5.50	3.50	3.39	6.00
12	14.00	12.50	20.00	10.80	5.00	4.85	12.46

APPENDIX B: MANURE APPLICATION RATE CONVERSION

Site			Perdue		Elstow			
Watershed			B	C	B	C	D	E
Manure application rate	(gal ac^{-1})		7000	10000	5000	8000	5000	8000
	(m^3 ha^{-1})		78.6	112.3	56.2	89.9	56.2	89.9
Manure nutrient concentration	(mg L^{-1})	N	2795	2737	5455	4033	4799	4882
		P	786	594	427	564	698	405
		K	1450	1472	2352	1453	1825	1916
Manure nutrient rate [N-P-K]	(kg ha^{-1})	N	220	308	306	362	270	439
		P	62	67	24	51	39	36
		K	114	165	132	131	102	172
Manure nutrient rate [N-P_2O_5-K_2O]	(kg ha^{-1})	N	220	308	306	362	270	439
		P_2O_5	142	153	55	117	90	84
		K_2O	137	198	159	157	123	207

Note:

- 'gal': imperial gallon
- 1 (imperial gal ac^{-1}) = $4.54609*10^{-3}$ / 0.4046856 (m^3 ha^{-1})
  with the assumption of liquid hog manure density = 1 kg L^{-1} = 10^{-3} kg m^{-3}
- 1 m^3 = 10^3 L; 1 mg L^{-1} = 10^{-3} kg m^{-3}
- To obtain P_2O_5 value, multiply P by 2.3; to obtain K_2O value, multiply K by 1.2.
- Manure nutrient concentrations are mean value of sample from each specific watershed (Appendix F).

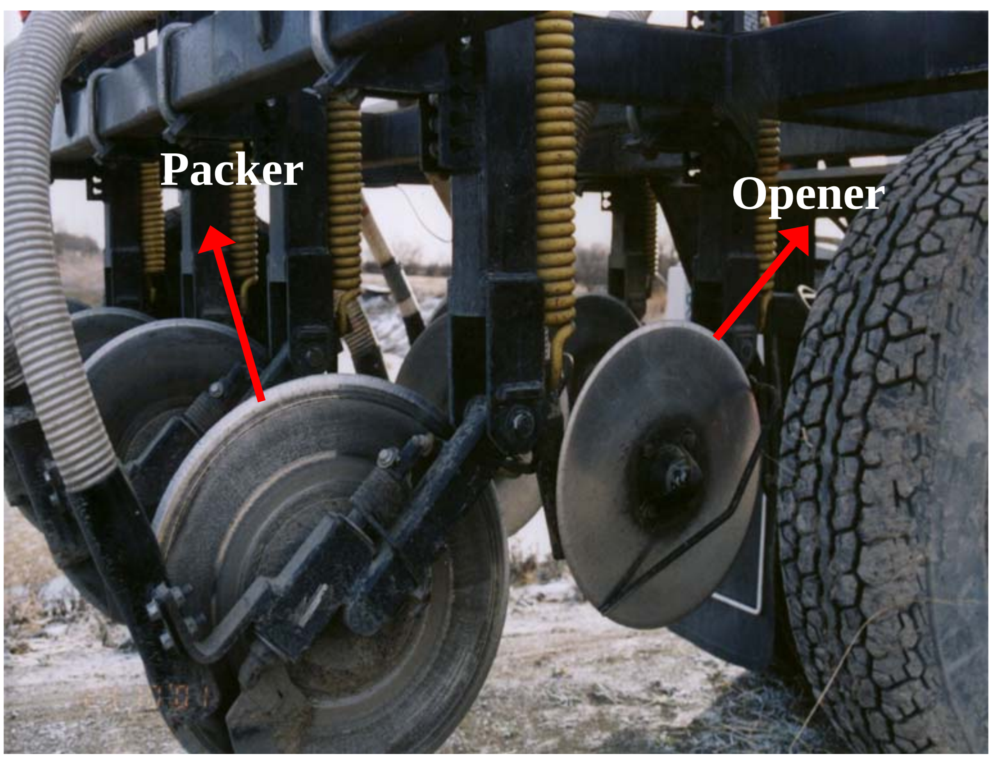
Example of nutrient rate conversion:

7,000 (imperial gal ac^{-1}) for watershed B at Perdue
= 7000 * $4.54609*10^{-3}$ / 0.4046856 (m^3 ha^{-1})
= 78.6 (m^3 ha^{-1})
= 1450 (mg K L^{-1}) * 78.6 (m^3 ha^{-1})
= 1450 * 10^{-3} (kg K m^{-3}) * 78.6 (m^3 ha^{-1})
= 114 (kg K ha^{-1}) * 1.2
= 137 (kg K_2O ha^{-1})

APPENDIX C: PHOTOS

C1: Perdue, Low Disturbance Manure Injector Using Disk-openers Followed by Knife Injectors on the Back of A Truck, Operated by SANDS LTD (October 1999)

C2: Low Disturbance Manure Injector Using Disc-openers in Watersheds B and E at Elstow (October 2001)



APPENDIX D: RAINFALL APPLICATION RATE (INTENSITY)

D1: Rainfall Application Rate – Perdue (1998, 2000)

Simulation date	Watershed	Slope position	Total applying time (min)	Total applying rain (mm)	Application rate (mm h^{-1})
17-Sep-98	A	shoulder	36.5	N/A	N/A
17-Sep-98	A	back	38.0	N/A	N/A
17-Sep-98	A	foot	42.0	N/A	N/A
22-Sep-98	B	shoulder	61.0	12.5	12.3
22-Sep-98	B	shoulder	61.0	17.3	17.0
23-Sep-98	B	back	45.1	27.9	37.1
23-Sep-98	B	back	45.1	17.3	23.0
22-Sep-98	B	foot	49.8	21.2	25.5
22-Sep-98	B	foot	49.8	22.1	26.7
27-Sep-98	C	shoulder	44.7	26.4	35.5
27-Sep-98	C	shoulder	44.7	29.3	39.4
27-Sep-98	C	back	39.1	27.9	42.8
27-Sep-98	C	back	39.1	29.8	45.7
08-Oct-98	C	foot	38.0	26.9	42.5
08-Oct-98	C	foot	38.0	28.8	45.5
16-May-00	A	shoulder	45.3	44.0	58.2
16-May-00	A	shoulder	45.3	1.8	2.4
16-May-00	A	back	37.5	5.0	8.0
16-May-00	A	back	37.5	57.0	91.2
17-May-00	A	foot	51.6	57.0	66.3
17-May-00	A	foot	51.6	5.5	6.4
17-May-00	B	shoulder	31.7	30.5	57.7
17-May-00	B	shoulder	31.7	2.0	3.8
18-May-00	B	back	39.5	128.8	195.7
18-May-00	B	back	39.5	44.2	67.2
18-May-00	B	foot	46.2	98.1	127.4
18-May-00	B	foot	46.2	26.0	33.8
19-May-00	C	shoulder	38.1	51.9	81.8
19-May-00	C	shoulder	38.1	117.3	184.7
19-May-00	C	back	55.6	37.0	39.9
19-May-00	C	back	55.6	211.5	228.4
19-May-00	C	foot	74.6	94.2	75.8
19-May-00	C	foot	74.6	11.0	8.8

D2: Rainfall Application Rate – Elstow (2000, 2001)

simulation date	watershed	slope position	Total applying time (min)	Total applying rain (mm)	Application rate (mm h^{-1})
12-Oct-00	A	shoulder	34.75	9.62	16.60
12-Oct-00	A	back	26.5	N/A	N/A
12-Oct-00	A	foot	26.22	28.85	66.01
12-Oct-00	A	foot	26.22	288.46	660.10
18-Oct-01	B	shoulder	33.75	105.77	188.03
18-Oct-01	B	shoulder	33.75	217.31	386.32
18-Oct-01	B	back	26.38	96.15	218.70
18-Oct-01	B	back	26.38	153.85	349.92
19-Oct-01	B	foot	26.5	86.54	195.94
19-Oct-01	B	foot	26.5	82.69	187.23
10-Oct-00	C	shoulder	40.5	180.77	267.81
10-Oct-00	C	shoulder	40.5	284.62	421.65
10-Oct-00	C	back	31.7	92.31	174.71
10-Oct-00	C	foot	32.45	278.85	515.59
10-Oct-00	C	foot	32.45	294.23	544.03
28-Sep-00	D	shoulder	26	18.00	41.54
28-Sep-00	D	shoulder	26	272.12	627.96
28-Sep-00	D	back	26.75	15.30	34.32
28-Sep-00	D	back	26.75	288.46	647.02
28-Sep-00	D	foot	25.85	264.42	613.75
28-Sep-00	D	foot	25.85	151.92	352.63
2-Oct-00	E	shoulder	33.85	275.00	487.44
2-Oct-00	E	shoulder	33.85	278.85	494.26
2-Oct-00	E	back	28.9	278.85	578.92
2-Oct-00	E	back	28.9	278.85	578.92
2-Oct-00	E	foot	29.58	153.85	312.06
2-Oct-00	E	foot	29.58	163.46	331.56

D3: Rainfall Application Rate – Elstow (2002)

simulation date	watershed	slope position	Total applying time (min)	Total applying rain (mm)	Application rate (mm h^{-1})
16-May-02	A	shoulder	35.5	130.77	221.02
16-May-02	A	shoulder	35.5	55.77	94.26
16-May-02	A	back	38.58	148.08	230.29
16-May-02	A	back	38.58	211.54	328.99
17-May-02	A	back-2	33.32	138.46	249.33
17-May-02	A	back-2	33.32	90.38	162.76
16-May-02	A	foot	43.07	192.31	267.90
16-May-02	A	foot	43.07	109.62	152.70
15-May-02	B	shoulder	36.08	98.08	163.10
15-May-02	B	shoulder	36.08	145.19	241.45
15-May-02	B	back	36.47	58.65	96.50
15-May-02	B	back	36.47	127.88	210.39
21-May-02	B	back-2	33.83	140.38	248.98
21-May-02	B	back-2	33.83	140.38	248.98
15-May-02	B	foot	30.67	230.77	451.46
15-May-02	B	foot	30.67	46.15	90.29
13-May-02	C	shoulder	34.82	142.31	245.22
13-May-02	C	shoulder	34.82	117.31	202.14
13-May-02	C	back	40.45	123.08	182.56
13-May-02	C	back	40.45	163.46	242.46
21-May-02	C	back-2	51.6	153.85	178.89
21-May-02	C	back-2	51.6	228.85	266.10
13-May-02	C	foot	29.95	61.54	123.28
8-May-02	D	shoulder	37.18	105.77	170.69
8-May-02	D	shoulder	37.18	159.62	257.58
8-May-02	D	back	32.62	272.12	500.52
8-May-02	D	back	32.62	118.27	217.54
23-May-02	D	back-2	52.53	215.38	246.01
23-May-02	D	back-2	52.53	216.35	247.11
9-May-02	D	foot	32.75	163.46	299.47
9-May-02	D	foot	32.75	132.69	243.10
14-May-02	E	shoulder	42.53	87.50	123.44
14-May-02	E	shoulder	42.53	104.81	147.86
14-May-02	E	back	55	186.54	203.50
14-May-02	E	back	55	80.77	88.11
17-May-02	E	back-2	58.25	128.85	132.72
17-May-02	E	back-2	58.25	225.00	231.76
14-May-02	E	foot	35.07	61.54	105.28
14-May-02	E	foot	35.07	186.54	319.14

APPENDIX E: EXAMPLES OF RUNOFF RATE CALCULATION

Example 1:

At back slope position simulation of watershed A in Elstow 2000, 2L sample was collected at 15 minutes after runoff started, and the total runoff volume for the time interval 15~20 minute was 9.28 L. For the time interval 10~15 minute, the runoff rate was 1.28 L/min at the representative time 12.5 minute. For the time interval 15~20 minute, the runoff rate was 1.86 L/min at the representative time 17.5 minute.

The representative time for sampling period = 2/9.28 * (20-15) * 1/2 + 15 = 15.54 min

Runoff rate at 15.54 minutes = (1.86-1.28)(15.54-12.5)/(17.5-12.5) + 1.28 = 1.63 L/min

Example 2:

At back slope position simulation of watershed A in Elstow 2000, 0.415 L sample was collected at 25 minutes after runoff started, and the total runoff volume for the time interval 20~25 minute was 12.18 L. For the time interval 15~20 minute, the runoff rate was 1.86 L/min at the representative time 17.5 minute. For the time interval 20~25 minute, the runoff rate was 2.44 L/min at the representative time 22.5 minute.

The representative time for sampling period = 0.415 / 12.18 * (25-20) * 1/2 + 25
= 25.09 min

Runoff rate at 25.09 minutes = (2.44-1.86) (25.09-17.5) / (22.5-17.5) + 1.86

= 2.74 L/min

APPENDIX F: MANURE CHEMISTRY

F1: Manure chemistry – Perdue

H_20 Extraction (Wt + 20 mL H_2O)

Watershed	pH	Wt used (g)	NH_4-N	OP	Cl^-
			(mg L^{-1})		
B-Top	7.61	5.1985	2158.6	106.95	967.5
B-Bottom	7.88	5.1993	1714.0	74.15	512.3
C-Top	7.89	5.1135	1736.9	61.84	701.3
C-Bottom	7.88	5.4887	1947.8	46.88	829.9
Average	7.82	5.25	1889.3	72.46	752.8
SD	0.14	0.16	208.1	25.56	193.7

Note:
- SD: standard deviation

H_2SO_4 Digest (Based on 75 ml of digest)

Watershed	TN	TP	Ca	Mg	K	Na
	mg L^{-1} of manure or sample					
B-Top	2899.69	1067.57	1141.14	357.36	1431.68	390.39
B-Bottom	2689.87	503.62	447.83	213.04	1468.12	387.68
C-Top	2703.34	534.52	499.37	206.56	1467.31	395
C-Bottom	2771.5	652.73	678.83	233.07	1477.41	400.36
Average	2766.1	689.61	691.79	252.51	1461.13	393.36
SD	96.0	260.04	315.5	70.81	20.16	5.56

Note:
- SD: standard deviation

F2: Manure chemistry – Elstow

H_20 Extraction (Wt + 20 mL H_2O)

Watershed	pH	EC	NH_4-N	OP	Cl^-
		($mS\ cm^{-1}$)		($mg\ L^{-1}$)	
B	7.3	18.58	4094.1	178.2	187.8
C	7.7	24.5	3339.5	184.8	141.7
C	7.6	20.9	2147.3	139.6	113.6
D	7.9	29.6	3521	157.8	147.4
D	7.3	27.3	3498.6	174.3	148.1
E	7.4	29.6	3590.5	216.3	147.5
E	7.7	24	4030.1	232.1	172.2
E	7.5	29.8	3596.6	188.4	156.2
E	7.8	25.6	3739.2	180	156.7
PSC	7.7	25.7	3837.7	166.9	164.7
PSC	7.5	26.5	4726.5	180.9	196.7
PSC	7.5	27.1	3389.8	179.5	146.2
Average	7.6	25.8	3625.9	181.6	156.6
SD	0.2	3.4	603.4	24.2	22.0

Note:
- SD: standard deviation

H_2SO_4 Digest (Based on 75 ml of digest)

Watershed	TN	TP	Ca	Mg	K	Na
	mg L^{-1} of manure or sample					
B	5454.9	426.7	520.1	82	2352.4	742.6
C	4414.5	505.1	486.7	197.7	1660	495.3
C	3651	623.8	553.3	268.7	1246.9	393.4
D	4474.9	448.4	403.6	170.4	1760.9	537.4
D	5122.4	948.1	747.4	395.4	1888.5	571.4
E	4433.7	303.2	264.5	38.3	1622.5	514.4
E	5333.1	381.8	364.6	47.3	2121.2	668
E	4393.9	297.9	275.5	54.2	1869.3	591.4
E	5368.2	637.9	534.1	244.5	2049	618.8
PSC	5084.2	460.2	464.9	134.4	1974	578.6
PSC	6830	1425.6	1210	547.5	2401.2	748.9
PSC	4891	520.7	483.9	179.5	1758.2	533.6
Average	4954.32	581.6	525.7	196.66	1892.0	582.82
SD	794.16	318.5	251.7	152.48	321.0	102.07

Note:
- PSC: Prairie Swine Centre, the supply source of hog manure.
- SD: standard deviation

APPENDIX G: WATER CHEMISTRY (ORIGINAL DATA) OF RUNOFF AND SIMULATED RAIN

G1: Water Quality – Perdue

(a) Before manure addition (1998)

Watershed	Slope position	Date	Sampling time	TP	OP	NH_4-N	NO_3-N	DOC	Cl^-	Total coliform	Fecal coliform
			(min)			(mg /L)				(ct/100mL)	
A	shoulder	17-Sep-98	15	2.73	0.11	0.258	0.09	8.2	3.6		
A	back	17-Sep-98	5	3.37					3.8	3650000	
A	back	17-Sep-98	15	2.58	0.62	0.289	0.97	6.9	3.5	1700000	
A	back	17-Sep-98	25	2.95					3	548000	
A	back	17-Sep-98	35						2.7		
A	foot	17-Sep-98	15	1.59	0.044	0.306	0.124	8.3	3.4		
B	shoulder	22-Sep-98	15	0.028	<0.002	0.238	0.153	5.7	3.9		
B	back	22-Sep-98	5	3.83					4.2	548000	
B	back	22-Sep-98	15	2.85	0.045	0.3	0.143	3.9	3.3		
B	back	22-Sep-98	25	0.846					3.7	116000	
B	back	22-Sep-98	35						3		
B	foot	22-Sep-98	15	0.765	0.022	0.102	0.374	6.4	5		
C	shoulder	27-Sep-98	15	2.23	0.002	0.162	0.054	3.9	3.3		
C	back	27-Sep-98	5	2.62					2.7	34500	
C	back	27-Sep-98	15	2.08	0.019	0.137	0.07	5.1	2.7	17200	
C	back	27-Sep-98	25	1.99					2.8	17900	
C	back	27-Sep-98	35						3.3		
C	foot	8-Oct-98	15	1.25	0.056	0.097	0.159	6.5	3.6		
Simulated Rain		17-Sep-98		0.044	0.006	0.181	0.028	2.38	3.28	24200	
Simulated Rain		22-Sep-98		0.02	0.002	0.184	0.034	2.41	3.46	13500	
Simulated Rain		22-Sep-98		0.013	0.002	0.155	0.036	5.47	3.22	3300	
Simulated Rain		27-Sep-98		0.012	0.002	0.187	0.038	2.53	3.17	359	
Simulated Rain		8-Oct-98		0.014	0.002	0.138	0.064	2.49	3.3	3	

(b) After manure addition (2000)

Watershed	Slope position	Date	Sampling time	TP	OP	NH_4-N	NO_3-N	DOC	Cl^-	Total coliform	Fecal coliform
			(min)	(mg /L)						(ct/100mL)	
A	shoulder	16-May-00	15	0.671	0.022	0.394	0.79	5.8	25.3		
A	back	16-May-00	5	1.01					25.6		20
A	back	16-May-00	15	0.361	0.033	0.453	0.86	6.1	25.4		249
A	back	16-May-00	25	1.22					25.3		2160
A	foot	17-May-00	15	0.792	0.06	0.417	0.61	6.8	25.4		
B	shoulder	17-May-00	15	3.05	0.798	2.31	2.13	7.4	26.6		
B	back	18-May-00	5	6.76					30.4		35
B	back	18-May-00	15	1.53	1.1	1.69	2.34	7.7	31.6		17
B	back	18-May-00	25	5.23					29.9		285
B	foot	18-May-00	15	1.37	0.909	1.28	11	12.5	31.7		
C	shoulder	19-May-00	15	0.822	0.296	0.586	3.15	6.9	34.6		
C	back	19-May-00	5	2.8					33.7		2040
C	back	19-May-00	15	1.23	0.148	0.894	5.21	7.1	34.2		127
C	back	19-May-00	25	3.79					33.3		151
C	foot	19-May-00	15	0.574	0.242	0.582	2.51	6.2	34		
Simulated Rain		16-May-00		0.006	0.003	0.479	0.695	4.31	29.1		<1
Simulated Rain		19-May-00		0.006	0.005	0.396	2.31	5.39	33.3		<1

G2: Water quality – Elstow

(a) Before manure application (2000 & 2001)

Watershed	Slope position	Date	Sampling time	TP	OP	NH_4-N	NO_3-N	DOC	Cl^-	Fecal coliform
			(min)			(mg /L)				(ct/100mL)
A	shoulder	12-Oct-00	15	0.203	0.046	0.202	0.352	7.2	9.9	
A	back	12-Oct-00	5	0.560					10.0	<1
A	back	12-Oct-00	15	0.402	0.100	0.229	0.508	7.5	8.0	<1
A	back	12-Oct-00	25	0.466					7.2	<1
A	foot	12-Oct-00	15	0.528	0.130	0.241	0.834	5.0	6.8	
B	shoulder	18-Oct-01	15	0.259	0.047	0.253	1.890	6.1	24.5	
B	back	18-Oct-01	5	0.972					27.5	<1
B	back	18-Oct-01	15	0.118	0.072	0.239	1.750	6.3	24.2	<1
B	back	18-Oct-01	25	0.369						<1
B	foot	18-Oct-01	15	0.227	0.141	0.511	1.410	9.2	28.4	
C	shoulder	10-Oct-00	15	0.281	0.038	0.208	0.202	6.4	8.5	
C	back	10-Oct-00	5	0.398					17.0	<1
C	back	10-Oct-00	15	0.229	0.065	0.228	0.547	8.8	11.5	<1
C	back	10-Oct-00	25	0.215					8.9	<1
C	foot	10-Oct-00	15	0.512	0.197	0.240	2.710	9.0	9.8	
D	shoulder	28-Sep-00	15	0.289	0.055	0.247	0.184	4.5	6.9	
D	back	28-Sep-00	5	0.567					10.1	<1
D	back	28-Sep-00	15	0.240	0.082	0.253	0.288	5.1	7.6	<1
D	back	28-Sep-00	25	0.395					6.8	1
D	foot	28-Sep-00	15	0.647	0.187	0.312	1.400	5.4	9.0	
E	shoulder	2-Oct-00	15	0.133	0.052	0.204	0.268	4.2	7.9	
E	back	2-Oct-00	5	0.475					10.8	1
E	back	2-Oct-00	15	0.433	0.165	0.233	0.540	5.1	8.1	<1
E	back	2-Oct-00	25	0.190					7.8	<1
E	foot	2-Oct-00	15	0.205	0.137	0.222	0.727	5.4	8.6	
Simulated Rain		28-Sep-00		0.005	<0.002	0.203	0.081	4.4	6.5	<1
Simulated Rain		12-Oct-00		0.006	<0.002	0.186	0.089	2.3	7.0	<1
Simulated Rain		19-Oct-01		0.004	0.003	0.171	0.114	2.9	21.9	<1

(b) After manure application (2002)

Watershed	Slope position	Date	Sampling time	TP	OP	NH_4-N	NO_3-N	DOC	Cl^-	Fecal coliform	Total coliform
			(min)	(mg /L)						(ct/100mL)	
A	shoulder	16-May-02	15	0.128	0.058	0.264	0.488	7.4	23.6	<1	
A	back	16-May-02	5	0.453					19.9	<1	
A	back	16-May-02	15	0.140	0.092	0.409	0.199	7.9	20.7	<1	
A	back	16-May-02	25	0.239					17.5	<1	
A	back-2	17-May-02	5	0.485					21.85	<1	
A	back-2	17-May-02	15	0.193	0.065	0.288	0.178	7.22	20.7	<1	
A	back-2	17-May-02	25	0.337					23.2	<1	
A	foot	16-May-02	15	0.476	0.184	0.265	0.566	6.89	21.0	<1	
B	shoulder	15-May-02	15	0.263	0.03	0.424	0.222	4.64	24.29	<1	
B	back	15-May-02	5	0.688					19.04	<1	
B	back	15-May-02	15	0.251	0.058	0.525	0.259	4.66	23.83	<1	
B	back	15-May-02	25	0.663					23.4	<1	
B	back-2	21-May-02	5	1.42					20.99	<1	
B	back-2	21-May-02	15	0.626	0.083	0.649	0.181	4.97	22.93	<1	
B	back-2	21-May-02	25	1.13					20.51	<1	
B	foot	15-May-02	15	0.43	0.082	0.98	1.06	6.38	24.64	<1	
C	shoulder	13-May-02	15	0.331	0.126	0.851	2.08	8.43	29.86	<1	
C	back	13-May-02	5	0.372					22.46	<1	
C	back	13-May-02	15	0.162	0.072	0.632	0.463	11.9	20.73	<1	
C	back	13-May-02	25	0.254					22.46	<1	
C	back-2	21-May-02	5	0.397					27.94	<1	
C	back-2	21-May-02	15	0.213	0.061	0.4	0.3	6.41	22.35	<1	
C	back-2	21-May-02	25	0.35					23.4	<1	
C	foot	13-May-02	15	0.3	0.13	1.29	3.67	13.6	32.08	<1	
D	shoulder	8-May-02	15	0.162	0.025	0.37	0.214	4.47	24.35		<1
D	back	8-May-02	5	0.734					32.39		254
D	back	8-May-02	15	0.188	0.104	0.686	0.672	7.44	24.01		<1
D	back	8-May-02	25	0.579					20.95		<10
D	back-2	23-May-02	5	0.465					49.41	<1	34400
D	back-2	23-May-02	15	0.207	0.093	0.37	1.55	7.61	41.52	<1	131
D	back-2	23-May-02	25	0.324					29.02	<1	48800
D	foot	8-May-02	15	0.511	0.132	2.33	1.75	15.2	24.54		429
E	shoulder	14-May-02	15	0.097	0.045	0.845	1.62	7.34	28.91	<1	
E	back	14-May-02	5	0.173					23.53	<1	
E	back	14-May-02	15	0.083	0.04	0.394	0.17	4.69	22.16	<1	
E	back	14-May-02	25	0.128					22.71	<1	
E	back-2	17-May-02	5	0.356					23.33	<1	
E	back-2	17-May-02	15	0.246	0.057	0.483	0.244	6.62	21.23	<1	
E	back-2	17-May-02	25	0.244					23.74	<1	
E	foot	14-May-02	15	0.165	0.028	0.32	0.13	4.69	25.07	<1	
Simulated Rain		8-May-02		0.004	<0.002	0.198	0.086	2.5	23.0	<1	
Simulated Rain		21-May-02		0.005	<0.002	0.183	0.060	2.8	21.7	<1	

APPENDIX H: RUNOFF RATE

H1: Runoff Rate – Perdue

(a) Before manure addition (1998)

Watershed	Slope position	Rep time (min)	Runoff rate (mm min^{-1})
A	shoulder	2.5	0.40
		7.5	0.56
		11.3	0.50
		13.8	0.39
		17.5	0.48
		22.5	0.40
A	back	2.5	0.40
		7.5	0.51
		11.3	0.60
		13.8	0.57
		17.5	0.57
		22.5	0.54
		27.8	0.54
		32.8	0.54
A	foot	2.5	0.13
		7.5	0.26
		12.5	0.33
		16.5	0.41
		19.0	0.41
		22.0	0.51
		26.3	0.45
B	shoulder	2.5	0.17
		7.5	0.14
		12.5	0.23
		17.5	0.21
		22.5	0.25
		27.5	0.26
		32.5	0.28

Watershed	Slope position	Rep time (min)	Runoff rate (mm min^{-1})
B	back	2.5	0.04
		6.3	0.11
		8.8	0.35
		10.8	1.25
		13.3	0.49
		16.5	1.28
		19.0	0.77
		22.5	0.03
		27.2	0.06
		31.4	0.42
		34.3	1.08
B	foot	2.5	0.03
		7.5	0.02
		12.5	0.02
		16.7	0.03
		26.7	0.08
C	shoulder	2.5	0.26
		7.5	0.55
		12.5	0.56
		17.5	0.96
		22.5	0.75
C	back	2.5	0.59
		7.5	0.72
		12.5	0.81
		17.5	1.06
		22.5	1.20
		27.5	1.25
		32.5	1.26
C	foot	2.5	0.03
		7.5	0.05
		12.5	0.43
		17.5	0.41
		22.5	0.44

Note:
- ‘Rep time’ refers to the representative time of each sampling period after runoff initiation.
- mm min^{-1} = L min^{-1} m^{-2}

(b) After manure addition (2000)

Watershed	Slope position	Rep Time (min)	Runoff rate (mm min^{-1})
A	shoulder	2.5	0.04
		7.5	0.08
		12.5	0.11
		17.5	0.17
		22.5	0.18
		27.5	0.24
A	back	2.5	0.07
		7.5	0.16
		12.5	0.19
		19.3	0.24
		24.3	0.41
		27.5	0.31
A	foot	2.5	0.06
		7.5	0.12
		12.5	0.14
		18.0	0.15
		23.0	0.15
		27.5	0.18
B	shoulder	2.5	0.09
		7.5	0.12
		12.5	0.13
		18.0	0.12
		23.0	0.13
		27.5	0.18
B	back	2.5	0.06
		7.5	0.21
		12.5	0.19
		17.5	0.20
		22.5	0.26
		27.5	0.38

Watershed	Slope position	Rep Time (min)	Runoff rate (mm min^{-1})
B	foot	2.5	0.04
		7.5	0.10
		12.5	0.10
		18.0	0.17
		23.0	0.19
		27.5	0.24
C	shoulder	2.5	0.07
		7.5	0.12
		12.5	0.16
		17.5	0.18
		22.5	0.20
		27.5	0.20
C	back	2.5	0.01
		7.5	0.08
		12.5	0.13
		18.5	0.13
		23.5	0.16
		27.5	0.18
C	foot	2.5	0.01
		7.5	0.07
		12.5	0.09
		20.0	0.09
		27.5	0.11

Note:
- ‘Rep time’ refers to the representative time of each sampling period after runoff initiation.
- mm min^{-1} = L min^{-1} m^{-2}

H2: Runoff Rate – Elstow

(a) Before manure addition (2000 & 2001)

Watershed	Slope Position	Rep time (min)	Runoff rate (mm min^{-1})	Watershed	Slope Position	Rep time (min)	Runoff rate (mm min^{-1})
A	shoulder	2.5	0.05	C	foot	2.5	0.24
		7.5	0.37			7.5	0.29
		12.5	0.84			12.5	0.28
		17.5	1.44			17.5	0.29
		22.5	1.51			22.5	0.49
A	back	2.5	0.76	D	shoulder	2.5	0.99
		7.5	0.95			7.5	1.25
		12.5	1.42			12.5	1.26
		17.5	2.06			17.5	1.75
		22.5	2.71			22.5	2.26
A	foot	2.5	0.60	D	back	2.5	1.71
		7.5	0.59			7.5	2.40
		12.5	0.91			12.5	3.45
		17.5	1.38			17.5	3.71
		22.5	1.91			22.5	4.29
B	shoulder	7.5	0.11	D	foot	2.5	0.96
		17.0	0.56			7.5	1.33
		22.0	0.93			12.5	1.87
B	back	2.5	0.47			17.5	2.18
		7.5	0.40			22.5	2.67
		12.5	0.40	E	shoulder	2.5	1.03
		17.5	0.44			7.5	2.06
		22.5	0.91			12.5	2.51
B	foot	2.5	2.04			17.5	2.47
		7.5	1.07			22.5	2.73
		12.5	0.51	E	back	2.5	0.33
		18.0	0.37			7.5	0.67
		23.0	0.39			12.5	1.71
C	shoulder	2.5	0.37			17.5	2.24
		7.5	0.67			22.5	3.27
		12.5	0.56	E	foot	5	0.79
		17.5	0.60			12.5	1.11
		22.5	0.62			17.5	1.13
C	back	2.5	0.53			22.5	1.13
		7.5	0.99				
		12.5	1.56				
		17.5	1.64				
		22.5	2.89				

Note:
- 'Rep time' refers to the representative time of each sampling period after runoff initiation.
- mm min^{-1} = L min^{-1} m^{-2}

(b) After manure addition (2002)

Watershed	Slope Position	Rep* time (min)	Runoff rate (mm min^{-1})
A	shoulder	2.5	1.07
		7.5	1.36
		12.5	1.69
		17.5	1.94
		22.5	2.28
A	back	2.5	1.44
		7.5	2.05
		12.5	2.47
		17.5	2.48
		22.5	2.80
	back-2	2.5	1.02
		7.5	1.47
		12.5	2.38
		17.5	2.64
		22.5	2.94
A	foot	3.15	0.66
		8.15	0.80
		12.5	1.06
		17.5	1.31
		22.5	1.14
B	shoulder	2.5	0.83
		7.5	1.82
		12.5	2.11
		17.5	2.08
		22.5	1.78
B	back	2.5	0.44
		7.5	0.82
		12.5	1.41
		17.5	1.89
		22.5	2.13
B	back-2	2.5	2.12
		7.5	1.94
		12.5	2.21
		17.5	2.39
		22.5	2.60
B	foot	2.5	0.25
		7.5	0.45
		12.5	0.97
		17.5	1.36
		22.5	1.37
C	shoulder	2.5	0.27
		7.5	0.50
		12.5	1.39
		17.5	1.66
		22.5	2.09
C	back	2.5	0.84
		7.5	1.02
		12.5	1.25
		17.5	1.12
		22.5	1.19
C	back-2	2.5	0.66
		7.5	0.98
		12.5	1.30
		17.5	1.54
		22.5	1.87
C	foot	2.5	0.64
		7.5	0.68
		12.5	0.97
		17.5	1.16
		22.5	1.41
D	shoulder	2.5	2.27
		7.5	2.33
		12.5	2.44
		17.5	2.67
		22.5	2.89
D	back	2.5	0.29
		7.5	0.56
		12.5	1.16
		17.5	1.04
		22.5	1.51
D	back-2	2.5	0.14
		7.65	0.34
		12.65	0.45
		17.5	0.57
		22.5	0.74
D	foot	2.5	0.09
		7.5	0.44
		12.5	0.71
		17.5	0.80
		22.5	1.00
E	shoulder	2.5	0.33
		7.5	0.45
		12.5	0.70
		17.5	0.75
		22.5	0.84
E	back	2.5	0.38
		7.5	0.44
		12.5	0.49
		17.5	0.52
		22.5	0.60
E	back-2	2.5	0.78
		7.5	0.66
		12.5	0.82
		17.5	0.82
		22.5	0.31
E	foot	2.5	0.58
		7.5	1.00
		12.5	1.32
		17.5	1.32
		22.5	1.57

‘Rep time’ refers to the representative time of each sampling period after runoff initiation.; mm min^{-1} = L min^{-1} m^{-2}

APPENDIX I: SOIL NUTRIENT SUPPLY RATES

I1: Soil nutrient supply rates – Perdue

Year	Watershed	Slope position	Fe	Mn	Cu	Zn	B	Pb	Cd
			$\mu g\ 10\ cm^{-2}\ 24\ h^{-1}$						
1998	A	shoulder	2.5	40.1	0.8	0.5	3.0	0.3	< 0.2
	A	back	3.0	21.7	0.7	0.8	4.3	0.3	< 0.2
	A	foot	3.1	32.4	0.5	2.0	2.0	0.4	< 0.2
	B	shoulder	2.2	21.6	0.8	12.7	2.0	0.3	< 0.2
	B	back	3.6	31.4	0.6	1.5	3.5	0.4	< 0.2
	B	foot	6.2	65.4	1.0	7.1	2.2	0.7	< 0.2
	C	shoulder	3.5	20.4	0.8	10.4	4.2	0.2	< 0.2
	C	back	3.0	19.7	0.6	2.6	4.1	0.2	< 0.2
	C	foot	2.7	21.1	0.4	0.7	5.8	0.2	< 0.2
2000	A	shoulder	2.0	7.5	0.5	0.5	4.9	0.0	0.1
	A	back	3.0	20.6	0.5	0.9	1.3	0.2	0.1
	A	foot	3.0	29.6	0.3	1.7	1.9	0.2	0.1
	B	shoulder	2.0	12.5	0.3	1.5	1.5	0.0	0.5
	B	back	3.0	33.1	0.8	2.0	2.7	0.2	0.1
	B	foot	5.0	29.6	0.4	1.0	3.0	0.1	0.3
	C	shoulder	2.0	6.1	0.5	0.8	3.4	0.0	0.2
	C	back	4.0	10.8	0.6	2.1	1.9	0.1	0.3
	C	foot	1.0	11.3	0.4	3.4	0.9	0.0	0.4
Method Detection Limits:			0.4	0.2	0.2	0.2	0.2	0.2	0.2

Note:
- BEFORE (before manure application): year 1998
- AFTER (after manure application): year 2000

I2: Soil nutrient supply rates – Elstow

Year	Watershed	Slope position	Fe	Mn	Cu	Zn	B	Pb	Cd
			$\mu g\ 10\ cm^{-2}\ 24\ h^{-1}$						
2000	A	shoulder	4.9	53.4	0.4	1.7	2.2	0.4	< 0.2
	A	back	4.9	40.6	0.5	1.8	2.5	0.5	< 0.2
	A	foot	2.7	8.1	< 0.2	0.9	2.7	0.3	< 0.2
2001	B	shoulder	1.4	32.2	< 0.2	0.5	1.6	< 0.2	< 0.2
	B	back	3.0	46.8	0.4	2.0	5.1	0.4	< 0.2
	B	foot	12.4	26.6	0.2	0.8	2.1	< 0.2	< 0.2
2000	C	shoulder	3.5	36.1	0.4	2.5	3.1	0.3	< 0.2
	C	back	2.4	21.5	0.3	1.6	3.4	0.3	< 0.2
	C	foot	32.7	28.3	0.5	3.3	3.3	0.5	< 0.2
2000	D	shoulder	1.8	16.4	0.2	0.6	1.5	0.2	< 0.2
	D	back	6.6	43.7	0.4	2.3	3.1	0.5	< 0.2
	D	foot	54.7	27.5	0.5	2.1	2.2	0.5	< 0.2
2000	E	shoulder	1.7	18.3	0.2	0.9	3.1	< 0.2	0.2
	E	back	2.7	26.9	0.3	1.4	2.7	0.3	< 0.2
	E	foot	23.4	47.1	0.4	2.5	1.8	0.5	< 0.2
2002	A	shoulder	2.0	35.6	0.2	1.0	1.8	0.2	< 0.2
	A	back	3.4	45.6	0.4	1.8	2.6	0.4	< 0.2
	A	foot	3.2	32.0	0.4	1.4	2.8	0.2	< 0.2
2002	B	shoulder	5.0	30.4	0.6	0.8	2.2	0.2	< 0.2
	B	back	1.8	26.4	0.2	0.8	2.0	0.2	0.2
	B	foot	4.0	14.2	0.2	1.0	3.0	0.2	< 0.2
2002	C	shoulder	6.8	10.0	0.4	0.6	2.6	0.2	0.2
	C	back	5.0	20.0	0.2	1.2	2.0	0.2	< 0.2
	C	foot	5.4	22.4	0.2	1.0	1.4	0.2	0.2
2002	D	shoulder	2.8	26.4	0.2	1.0	1.6	0.2	< 0.2
	D	back	4.4	6.0	0.2	0.6	1.2	< 0.2	< 0.2
	D	foot	7.0	18.0	0.2	0.8	2.4	< 0.2	0.2
2002	E	shoulder	2.0	21.8	0.2	0.8	0.8	< 0.2	0.2
	E	back	6.2	34.4	0.4	2.0	2.0	0.2	0.2
	E	foot	5.6	16.6	0.2	0.6	1.8	< 0.2	0.2
2002	A	back-2	2.2	8.2	0.2	0.4	2.5	0.2	<0.2
2002	B	back-2	3.4	3.2	0.2	0.4	1.6	<0.2	0.2
2002	C	back-2	1.7	6.3	0.2	0.9	2.2	<0.2	<0.2
2002	D	back-2	3.1	12.3	0.2	0.7	1.2	0.2	0.2
2002	E	back-2	1.9	6.5	0.2	0.7	2.8	0.2	<0.2
Method Detection Limits:			0.4	0.2	0.2	0.2	0.2	0.2	0.2

Note:
- BEFORE (before manure application): year 2000 for watersheds ACDE and year 2001 for watershed B.
- AFTER (after manure application): year 2002 for watersheds ABCDE